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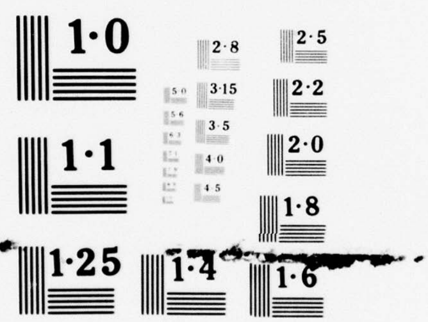

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NWC TP 5922

Color Coding
An Annotated Bibliography

by
Dan W. Wagner
Weapons Systems Analysis Division
Systems Development Department

MARCH 1977

Naval Weapons Center
CHINA LAKE, CALIFORNIA 93555

Naval Weapons Center

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R. G. Freeman, III, RAdm., USN .... Commander

G. L. Hollingsworth .... Technical Director

FOREWORD

This selective review of color coding and color research literature was completed at the Naval Weapons Center, China Lake, CA, in 1976. The review was prepared in connection with Naval Air Systems Command sponsored research evaluating the potential uses of color displays in Naval aircraft cockpits. It is supported by AirTask No. A003P-3400/008B/7F55-525-000 under the direction of CDR Paul Chatelier (AIR-340F).

This report has been reviewed for technical accuracy by R. A. Erickson.

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(U) *Color Coding—An Annotated Bibliography*, by Dan W. Wagner. China Lake, Calif., Naval Weapons Center, March 1977. 58 pp. (NWC TP 5922, publication UNCLASSIFIED.)

(U) Fifty-seven documents were annotated for the purpose of presenting current information on color coding research and ~~color~~ applications. This selective review includes, in addition to a written summary of the work, figures and tables from many of the publications to graphically illustrate or clarify key points. (cont on p 3)

other applications of color for use on television.

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CONTENTS

ACKNOWLEDGMENT

Most of the figures and tables in this report are taken from or based on the work of many different authors published in a variety of journals, technical reports, and books. The figures and tables listed below are reproduced with the permission of the publisher. While permission to reproduce material from government publications is not required for purposes of the government, the author wishes to express his appreciation to all the authors and publishers for their cooperation.

American Psychological Assocation: Figures 3.1, 21.1, 21.2, 37.1, 37.2, 44.1, 45.1, 46,1, 46,2, 46.3, 47.1, 47.2; Table 2.1.

Honeywell, Inc.: Table 31.1.

John Wiley & Sons: Table 57.1.

Journal of the Optical Society of America: Figures 4.1, 25.1

Psychonomic Society, Inc.: Figures 6.1, 30.1.

Society for Information Display: Figures 49.1, 49.2, 49.3.

The Johns Hopkins University Press: Figures 28.1, 32.1, 32.2, 38.1, 43.1, 56.1; Tables 12.1, 12.2, 24.1, 24.2, 24.3, 38.1, 39.1, 39.2, 39.3, 39.4, 42.1, 42.2.

The Journal Press: Text table (item 9, p. 11).

INTRODUCTION

Numerous periodicals, books, and reports were reviewed for the purpose of obtaining current information on color coding research and other applications of color for use on television. Fifty-seven of the documents were selected for annotation. While the review is extensive, it is not comprehensive in the sense that much of the theoretical and conceptual work done in the area was passed over in favor of applied research.

The bibliography is arranged alphabetically by author. Also, an author index and subject index are provided in the back of the report. Organized in this manner, the review presents sufficient information and data to provide the reader with a general understanding of the scope of the work, the parameters investigated, the measures used, and the results of the salient color and color coding research to date.

BIBLIOGRAPHY

1. Allport, D. A. "Parallel Encoding Within and Between Elementary Stimulus Dimensions," *Perception and Psychophysics*, Vol. 10 (1971), pp. 104–108.

Color and form were investigated to determine their effect on performance when encoded simultaneously. The author found that color and form (numbers and geometric shapes) provided more correct responses than form-form (numbers within shapes) coding.

2. Alluisi, E. A., and P. F. Muller, Jr. "Verbal and Motor Responses to Seven Symbolic Visual Codes: A Study in S–R Compatibility," *J. Exp. Psych.*, Vol. 55 (1958), pp. 247–254.

To test S–R compatibility, Ss responded verbally and with key presses for comparison with seven types of visual codes: two types of numbers, three types of clock inclinations, ellipse-axis ratio and colors. They found that number codes were superior to the others with color codes a poor sixth. Verbal responses were more accurate, but motor responses were faster (see Table 2.1).

TABLE 2.1. Average Posttraining Self-Paced Performance With Seven Symbolic Codes.

Code	Speed[a]	Accuracy[b]	H_t[c]
AND 10400 Arabic Numerals	72.70 *75.11*	93.08 *99.57*	3.97 *4.38*
Symbolic Arabic Numerals	73.22 *77.91*	93.96 *97.00*	4.00 *4.20*
Simple Inclination	92.85 *107.14*	91.26 *99.03*	3.05 *3.02*
Clock Inclination	90.96 *103.33*	92.82 *98.67*	3.17 *3.14*
Binary Inclination	90.50 *103.26*	93.08 *97.73*	3.23 *3.13*
Ellipse-Axis Ratio	100.27 *122.99*	88.86 *99.37*	2.68 *2.56*
Color	100.05 *120.50*	88.94 *98.87*	2.74 *2.60*

Note.—Upper values are data for the motor responses of Exp. I; lower italicized values are data for the verbal responses of Exp. II.
[a] Mean time, in sec., per 100 responses.
[b] Percentage correct responses.
[c] Average rate of information transmission per *S*, in bits/sec.

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3. Anderson, N. S., and P. M. Fitts. "Amount of Information Gained During Brief Exposures of Numerals and Colors," *J. Exp. Psych.*, Vol. 56 (1958), pp. 362–369.

To increase coding alphabet size by increasing stimulus dimensionality, three presentation levels were studied: nine color patches, nine black numbers, and nine black numbers on color patches. In terms of transmitted information (bits) the color-numeric code was superior in that it transmitted more information than either unidimensional code (see Figure 3.1).

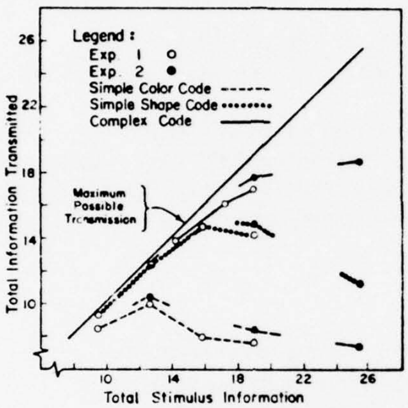


FIGURE 3.1. Mean Total Information Gained (Transmitted) per Message by Ss in Exp. I and II (N = 12 Different Ss in Each Experiment).

4. Bedford, R. E., and G. W. Wyszecki. "Wavelength Discrimination for Point Sources," *Opt. Soc. Amer., J.*, Vol. 48 (1958), pp. 129–135.

Wavelength discrimination curves for two subjects were measured under differing intensities and field sizes (1.5', 12', and 1^0). It was found that: (1) discriminability deteriorates with decreasing field size, and (2) maximum discriminability occurs at 420, 480, and 580 nm, while minimums occur at about 440 and 520 nm. It is worth noting that, while discrimination falls off with smaller field sizes, as long as the light source is sufficiently intense (2,000 trolands for the 1.5' field and 100 trolands for the 12' and 1^0 fields) it is still readily accomplished (see Figure 4.1).

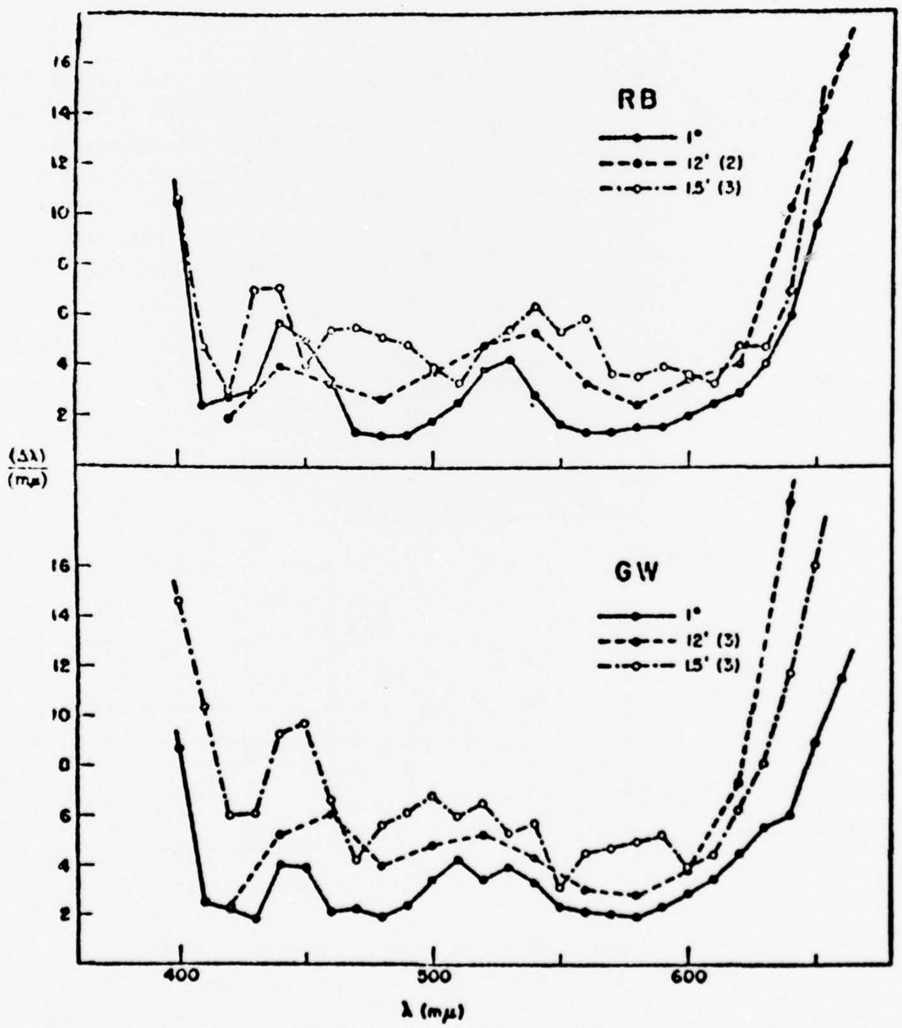


FIGURE 4.1. Dependence of Wavelength Discrimination on Field Size for Observers R. B. and G. W.

5. Bishop, H. P., and M. N. Crook. *Absolute Identification of Color for Targets Presented Against White and Colored Backgrounds*, Wright Air Development Division, Wright-Patterson Air Force Base, Ohio, WADD, March 1961. (Technical Report 60-611.)

Circular targets varying in size (10', 21', 1.4° and 5.7°), hue (B-461, BG-492, GB-500, G-521, GY-538, GY-552, YG-574, Y-588, O-606, and R-630 nm), purity (20, 30, 50, 70, and 100%) and target-background luminance ratios (2:1, 20:1, 200:1, 1:1, 1:2, and 1:5) were tested against red, green, blue, and white backgrounds of low to high purities to determine absolute identification of color targets. The study was very complex and in some cases precise experimental control was sacrificed to gain at least superficial data on the levels of the various parameters. Nevertheless, the findings should be useful, although additional studies are needed to validate specific results.

They found that: (1) the target size of 10' hindered performance more than the other three sizes; (2) the 10 colors mentioned above can be used with purities of 30% (40% recommended) and 70%, and luminance ratios of 2:1, 20:1, and 200:1, to provide an alphabet size of 30 colors against a white background (with moderate practice); (3) background color, low target purity and high background purity with low target luminance all make the task considerably more difficult (extensive training can help); (4) positive contrast targets (e.g., target 1 ftL, background 0.5 ftL) were detected more often than negative contrast targets (e.g., target 10 ftL, background 20 ftL). (See Figure 5.1.)

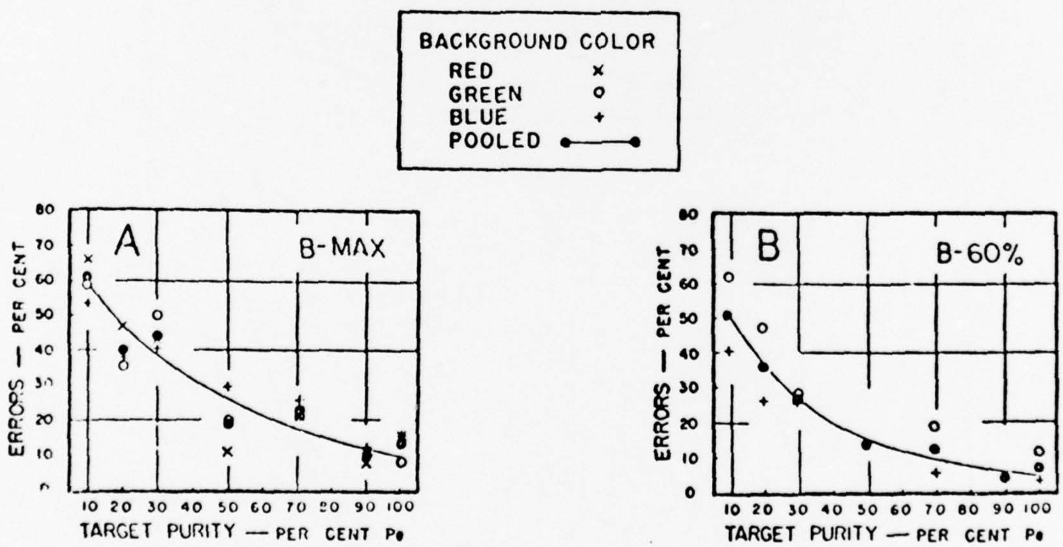


FIGURE 5.1. Percent Errors in Color Identification as a Function of Target Purity for Subject Group 3. The basic stimulus set of 28 items was tested against red, green, and blue backgrounds at 20%, 60%, and maximum purity, and white. The dotted branch of the curve for white background is based on regular and refresher runs combined. The data for 20%, 50%, and "90"% target purity are from subjects RT, LH, and DG, those for 10%, 30%, and 70% from subjects DM and ED, and those for maximum purity from all subjects combined. Experiment 1.

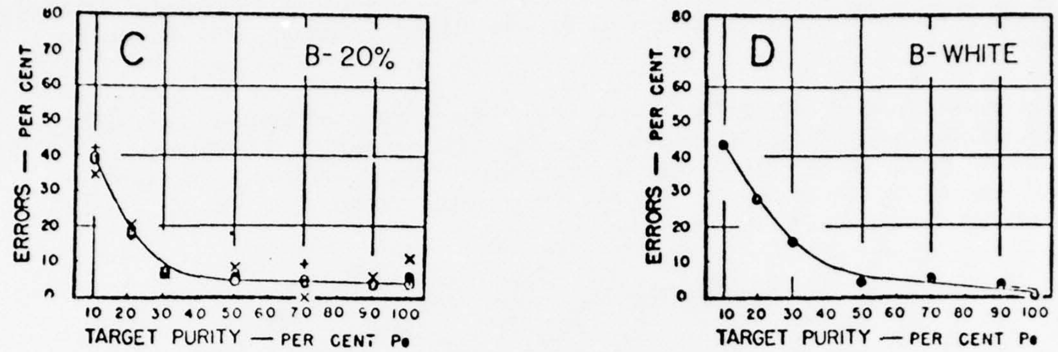


FIGURE 5.1. (Contd.)

6. Brooks, R. "Search Time and Color Coding," *Psychonomic Sci.*, Vol. 2 (1965), pp. 281–282.

Investigating the effects of color-coding on search time performance, the author presented subjects with five color-coded conditions and one no-color condition using alphanumerics seen in a matrix-on-paper display. The subjects' task was to search a display of 50 items and identify those items beginning with H, of which there were 10. The H items were underlined in red except for the "no-color" condition. Other letters were underlined with yellow, green, blue and/or violet, depending on which condition (0, 1, 2, 3, 4, 5 colors) was being tested.

The results show that the H items were found more quickly when they were color-coded (even when additional confusing colors were added) than when they were not. The report does not make it clear whether the lack of color or the lack of underlining increased response time for the "no color" condition (see Figure 6.1).

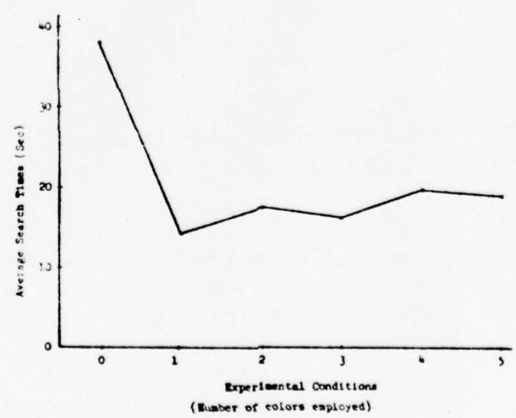


FIGURE 6.1. Average Search Times as a Function of the Number of Colors Employed.

7. Burdick, D. C., L. M. Chauvette, J. M. Duls, and A. E. Goins. Color Cathode Ray Tube Displays in Combat Information Centers. U. S. Naval Research Laboratory, 1965, Report No. 6348.

The authors reviewed both the literature on color-coding and state-of-the-art for color CRTs. Their findings are in accord with other surveys regarding color (e.g., Cook), but emphasize a cost-effectiveness approach. They conclude that color CRTs are probably worth the added cost for some tasks (i.e., locating). They include a list of coding methods, along with the effective number of levels for each code. (See list below.)

Coding modality	Coding level
Color	3–10
Size	3
Shape	
Alphanumeric and punctuation	50
Abstract	8–16
Suggestive	200–1000
Positions	
Linear	3–5
Two-dimensional	4–9
Three-dimensional	8–12
Orientation	4–8
Line width	2–3
Number (quantity)	4
Flicker	2–4
Intensity (brightness or grey scale)	2–4
Line length	2–4
Line type (dotted, dashed, etc.)	3–4
Focus of distortions	2
Depth	2–3
Motion	2–10

8. Cavonius, C. R., and R. Hilz. "Visual Performance After Preadaptation to Colored Lights," *J. Exp. Psych.*, Vol. 83 (1970), pp. 359–365.

Times required to detect a simple light and to discriminate the letter 'E', were compared as a function of wavelengths of preadapting light. They found that visual sensitivity to dim lights was best after exposure to red lights (680 nm), but acuity was best after orange (600 nm) (i.e., recovered more rapidly). They suggest red goggles are appropriate only when a visual task can be performed scotopically (dark-adapted eye-rod vision).

Also, recovery time is longer as preadapting luminance is brighter (18 sec for 220 ftL vs 7 sec for 2.7 ftL at 600 nm). The optimum appears to be to filter out light below 600 nm.

9. Chapanis, A., and R. M. Halsey. "Absolute Judgments of Spectrum Colors," *J. Psych.*, Vol. 42 (1956), pp. 99–103.

The authors investigated the number of colors that could be correctly coded. Subjects were trained to associate 10, 12, 15, and 17 colors with a number. Up to 550 trials were required for learning. They found that up to 15 colors could be coded with about 95% correct responses (see table below).

Number of hues	Correct responses, %
10	97.5
12	95.6
15	94.8
17	72.4

10. Christ, Richard E., and Gregory M. Corso. *Color Research for Visual Displays.* Office of Naval Research, Arlington Va. (ONR-CR213-102-3, July 1975.)

Ten experiments were conducted investigating color codes compared to achromatic codes of letters, digits, and geometric shapes. They measured response time and accuracy for choice, search and identification tasks using highly practiced subjects. The authors conclude that, generally:

(1) Color is not a clearly superior coding technique for the tasks studied. Geometric shapes provided comparable performance in most cases.

(2) Color is more advantageous when displays are complex and require distinguishing targets from clutter.

(3) Extended practice on the tasks reduces the differences between color and achromatic coding methods. (See Table 10.1.)

TABLE 10.1. Range of Percent Difference Scores for the Use of Color.[a]

Comparison achromatic code	Choice reaction task (response time)		Search/locate task (response time)		Identification task (response time)		Identification task (accuracy)	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Letters	-11.8	+36.5	-7.8	+27.3	+5.8	+27.4	-17.0	+2.9
Digits	-16.0	+29.2	-6.7	+21.9	-9.7	+17.3	-15.0	+0.2
Shapes	- 6.8	+16.4	-2.8	+12.9	-0.1	+15.7	-13.1	+1.1

[a] Positive scores indicate a gain, negative scores a loss with the use of color.

11. Christ, R. E., and W. H. Teichner. *Color Research for Visual Displays.* New Mexico State University, Las Cruces, N.M., July 1973. (JANAIR Report 73073.)

The report reviews the literature on the effects of color on visual search and identification performance. Generally: (1) If a target color is unique and known, it aids search and identification performance. (2) Color can be identified more accurately than size, brightness, and geometric shapes, but not alphanumerics. (3) Adding colors to familiar achromatic displays decreases accuracy. (4) Less time is required to find colors than all other achromatic codes. (5) Irrelevant colors increase search time for achromatic target features. (6) Knowing the target color decreases search time, particularly with increasing display density. (7) Search time may be reduced for "natural" representations compared to achromatic ones. (8) As the proportion of non-target colors increases, known-color advantage decreases and becomes a hindrance at about 0.70. (9) Not knowing the target color increases search time. (See Table 11.1.)

TABLE 11.1. Range of Percent Difference Scores for the Use of Color.[a]

	IDENTIFICATION TASK			SEARCH TASK		
	Minimum	Maximum	n[b]	Minimum	Maximum	n
Unidimensional						
Brightness	+29	+ 32	2	+43	+43	1
Size	- 6	+111	6	+40	+40	1
Geometric Shape	-38	+ 33	11	+ 6	+42	5
Other Shapes	0	+118	6	+30	+63	2
Letters	-29	- 15	6	+10	+ 7	2
Digits	-48	+ 26	17	- 3	+42	4
Multidimensional						
Size	-10	+176	7			0
Geometric Shape	-28	+202	15	+50	+53	3
Other Shapes	- 2	+ 62	12	+41	+69	6
Letters	+ 4	+ 46	4			0
Digits	-51	+ 19	6			0
Interference						
Size	-29	0	14			0
Geometric Shape	-42	+ 1	4	- 8	- 8	1
Other Shapes	-43	- 17	4	-10	- 3	2
Digits	-14	+ 2	7			0
Complete Redundancy						
Size	+22	+ 60	3	+32	+32	1
Brightness	+24	+104	2	+32	+32	1
Geometric Shape			0	+21	+32	2
Letters			0	+53	+63	2
Digits	+ 2	+ 2	1	+60	+74	3
Partial Redundancy						
Digits			0	-23	+73	20
Maps	+ 1	+ 1	1			0
Static-Ground Photo	+29	+ 29	1	+32	+47	1
Static-Aerial Photo	+ 2	+ 2	1	+17	+17	1
Dynamic-Aerial Film	+ 3	+ 3	1			0
Dynamic-Aerial TV	+ 3	+ 3	1	- 3	- 3	1

[a] Positive scores indicate a gain, negative scores a loss with the use of color.

[b] n = number of studies.

12. Christner, C. A., and H. W. Ray. "An Evaluation of the Effect of Selected Combinations of Target and Background Coding on Map-Reading Performance — Exp. V." *Hum. Factors*, Vol. 3 (1961), pp. 131–146.

The authors studied the relative effectiveness of various target-background coding combinations. Three target codes were: 8 colors, 8 numbers, and 8 shapes. Five background codes were: white, gray, 5 shades of gray for brightness coding, 5 colors, and 5 patterns (crosshatching, dots, etc.). All were measured under high and low densities, target numbers, and coding levels (4 or 8 colors, numbers, etc.). They found: (1) no difference for background codes; (2) target color codes better for search and count, but number codes do better for identification (target code interaction with task); and (3) when asked to rank 15 coding combinations, subjects preferred color targets. (Table 12.1 and 12.2.)

TABLE 12.1. Duncan Multiple Range Tests Applied to Geometric Means of Response Rates for Each of Five Tasks.

	Rank Orders [a]														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Identify:	20.65	20.59	19.93	19.80	19.53	17.21	16.81	16.60	16.55	16.53	16.33	16.27	16.09	15.99	14.95
Target	No.	No.	No.	No.	No.	Color	Color	Shape	Shape	Shape	Color	Shape	Color	Shape	Color
Background	All G.	Diff. G.	White	Patt.	Color	All G.	Patt.	White	Color	All G.	White	Diff. G.	Diff. G.	Patt.	Color
Locate:	9.38	9.36	9.19	905	8.95	7.67	7.48	7.30	7.16	7.07	6.87	6.82	6.77	6.70	6.54
Target	Color	Color	Color	Color	Color	No.	No.	No.	No.	No.	Shape	Shape	Shape	Shape	Shape
Background	Diff. G.	White	Patt.	All G.	Color	Patt.	Diff. G.	Color	White	All G.	All G.	Patt.	White	Diff. G.	Color
Count:	41.68	41.42	39.88	39.76	39.08	28.99	28.99	28.71	28.52	28.49	28.48	28.38	28.09	28.05	28.00
Target	Color	Color	Color	Color	Color	Color	No.	No.	Shape	Shape	Shape	No.	No.	No.	Shape
Background	Diff. G.	All G.	Patt.	White	Color	Diff. G.	Diff. G.	White	White	Color	All G.	All G.	Patt.	Color	Patt.
Compare:	7.54	7.25	7.13	7.13	7.10	7.09	7.02	7.01	6.98	6.96	6.96	6.87	6.66	6.58	6.54
Target	Color	No.	Color	Color	Shape	No.	Color	No.	No.	Color	Shape	No.	Shape	Shape	Shape
Background	Patt.	All G.	All G.	White	Diff. G.	Patt.	Diff. G.	Diff. G.	White	Color	All G.	Color	Color	White	Patt.
Verify:	20.37	20.20	20.13	20.12	20.08	20.06	19.65	19.64	19.32	19.21	19.06	18.89	18.86	18.72	18.24
Target	Color	Color	No.	No.	Shape	No.	Color	No.	No.	Shape	Color	Shape	Color	Shape	Shape
Background	All G.	White	All G.	Patt.	Diff. G.	Diff. G.	Diff. G.	White	Color	All G.	Patt.	White	Color	Patt.	Color

Notes:

(1) Numbers connected by line are not significantly different at $p < 0.05$.

(2) Abbreviations:

All G. = All gray.
Diff. G. = Different shades of gray.
Patt. = Patterned.
No. = Number.

[a] 1 = Most preferred; 15 = least preferred.

TABLE 12.2 Preferences by Ranks Averaged Over Five Subjects for Fifteen Code Combinations.[a]

Targets	Backgrounds: *Color*	*Mixed grays*	*Solid gray*	*White*	*Patterned*	*Average rank over backgrounds*
Color	6.8	3.5	4.1	3.5	3.9	4.36
Number	8.4	9.4	8.8	9.8	13.5	9.98
Enclosed shape	6.8	9.6	10.2	9.6	12.1	9.66
Average rank over targets	7.33	7.50	7.70	7.63	9.83	

[a] 1 = Most preferred; 15 = least preferred.

13. Conners, M. M. "Luminance Requirements for Hue Perception and Identification for a Range of Exposure Durations," *Opt. Soc. Amer., J.*, Vol. 60 (1970), p. 958.

Conners investigated small and large targets (2.5 and 64.5 min. of arc), stimuli exposure time (5–1413 msec), and short to long wavelength light effects on luminances required for several thresholds (e.g., hue perception and identification). The longer the exposure time, the lower the luminance needed. Also, larger targets take less time to detect than small targets. Longer wavelengths are seen at lower luminances.

14. Connolly, D. W., G. Spanier, and F. Champion. *Color Display Evaluation for Air Traffic Control.* U.S. Department of Transportation, Federal Aviation Administration, Washington, D.C., FAA, May 1975. (Report No. FAA-RD-75-39.)

The authors assessed the utility of color penetration-type CRT displays in air traffic control applications. They found that: (1) four colors could be identified with 97–99% accuracy; (2) where overlapping symbols were involved, color was three times more effective than monochrome; (3) color did not improve performance for altitude or future route predictions for separation rule violations. They note that considerable color CRT development is needed before it approaches the linearity, brightness, resolution, and tube life performance of available monochrome CRTs.

FIGURE 14.1. Symbols Used To Present Color Signals, Experiment 1 (Eight Times Actual Size).

TABLE 14.1. Errors of Color Identification.

Shown	Called					
	Red	Orange	Yellow	Green	Total	Percent
Red	X	21	0	0	21	2.9
Orange	9	X	10	0	19	2.6
Yellow	0	6	X	15	21	2.9
Green	0	0	6	X	6	0.8
				Grand Total =	67	2.3

Note: Each color was presented 720 times, 24 times for each of 30 observers.

15. Conover, D. W. and J. Kraft. *The Use of Color in Coding Displays.* Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, WADC 1958.

The authors investigated surface hues (Munsell) to determine the number of absolutely identifiable hues and an equal-discriminability scale of hues. They found that, while up to 16 hues could be discriminated by some subjects, no more than eight are recommended for applied purposes. Black, white, and gray may be added if contrast permits. The authors go on to *estimate* that no more than four colors need be used for coding on television. Table 15.1 shows the recommended sets for codes of 8, 7, 6, and 5 colors.

TABLE 15.1. Munsell Designations for the Recommended Color Symbol Sets—A, B, C, D.

Chart A		Chart B		Chart C		Chart D	
n*	p*	n	p	n	p	n	p
1R	999	5R	1008	1R	999	1R	999
9R	892	3YR	890	3YR	890	7YR	884
1Y	946	5Y	1128	9Y	1131	7GY	960
7GY	960	1G	1103	5G	1101	1B	1093
9G	1099	7BG	1095	5B	1087	5P	1007
5B	1087	7PB	1133	9P	1005		
1P	1135	3RP	1003				
3RP	1003						

* n = Book notation; p = Munsell production number.

16. Cook, Thomas C. *Color Coding — A Review of the Literature.* U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, Md., HEL, November 1974. (Tech Note 9-74.)

The author reviewed the color coding literature for visual displays and suggests that: (1) No more than nine surface hues—five for CRTs—be used, and the angular subtense should exceed 20 min. of arc. (2) Can be increased to 30 with two purities (30 and 70%) and three luminance levels (1, 10, and 100 ftL). (3) Six common colors are recommended: purple, blue, green, yellow, orange, and red (see Table 16.1). (4) Three codes (hue, brightness, and size) are better than two and two are better than one. (5) Numerics are better for identification and color is better for search and attention-gaining. Cook concludes that multicolor displays are advantageous in terms of faster response times or fewer errors or both; and that "validation studies" using actual color CRTs should be conducted as soon as possible.

TABLE 16.1. Recommended Chromatic Colors.

Color name	Munsell notation	Chromaticity coordinates	Dominant wavelength nonometers	Federal Spec. 595 equivalent (paint chips)
Purple	1.0 RP 4/19	X - .2884 Y - .2213	430	27144
Blue	2.5 PB 4/10	X - .1922 Y - .1673	476	15123
Green	5.0 G 5/8	X - .0389 Y - .8120	515	14260
Yellow	5.0 Y 8/12	X - .5070 Y - .4613	582	13538
Orange	2.5 YR 6/14	X - .6018 Y - .3860	610	12246
Red	5.0 R 4/14	X - .6414 Y - .3151	642	11105

17. Cornsweet, Tom N. *Visual Perception.* New York, Academic Press, 1970.

Cornsweet's book is aimed at developing an understanding of visual perception. He emphasizes the perception of color and brightness from both a physiological and psychophysical approach. A well-written, tutorial book for understanding color vision.

18. Ellis, B., G. J. Burrell, J. H. Wharf, and D. F. Hawkins. *The Format and Color of Small Matrix* Displays for Use in High Ambient Illumination. *Procurement Executive, Ministry of Defence, Farnborough, Hants, England. (Royal Aircraft Establishment Technical Report 75048, 1975.)*

Red and green alphanumeric matrices subtending 0.3^0 were seen under high ambient illumination to determine the effect on error rates. Two founts of 72 and 144 nits (21 and 42 ftL), simulating LED displays and placed in the black portion of a half black-half white background, were to be identified under an illuminance approaching 10^5 lux (9,250 ftL). It was found that people were more accurate with red than with green characters–94.2 vs. 84.1% correct. Performance was also better with the dimmer, contiguous fount than with the brighter but more widely separated (dot-space ratio) fount. It was also noted that females had fewer errors than did males (see Tables 18.1 and 18.2).

TABLE 18.1. Error Rates for Red and Green Displays.

	Normal vision		All subjects	
	E-R (%)	O-R (%)	E-R (%)	O-R (%)
Red	5.8	1.1	8.1	2.1
Green	15.9	5.6	22.7	10.4
	68 subjects average age 31.5 years		125 subjects average age 34.6 years	

E-R total error rate (mistakes and omissions)
O-R omission rate

TABLE 18.2. Relative Performance of Males and Females.

	Males		Females	
	E-R	O-R	E-R	O-R
Format test				
Size 1	12.8	2.8	5.3	1.3
Size 4	8.7	3.1	3.8	0.6
Colour test				
Red	6.3	1.2	3.6	0.6
Green	17.8	6.6	7.9	1.5

55 males. Average age 33.1 years
13 females. Average age 24.5 years
E-R total error rate (mistakes and omissions, %)
O-R omission rate (%)

19. Ericksen, C. W. *Multidimensional Stimulus Differences and Accuracy of Discrimination.* Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, WADC, 1954. (WADC TR 54-165.)

Size, hue, and brightness were investigated singly and in compounds to determine the effect of single and multidimensional stimuli upon the accuracy of absolute discriminability. Ericksen found that, when size, hue, and brightness were compounded as a tridimensional cue, the number of correct judgments was about double the number obtained when they were presented singly. (See Table 19.1.)

TABLE 19.1. Discrimination Accuracy for the Three Single and the Four Multidimensional Stimulus Series.

Stimulus Series	I_t*	Number of Stimuli Absolutely Discriminable	Average Percent Correct Judgments	
			Observed	Predicted
Size	2.84	7.19	47.5	
Hue	3.08	8.45	53.4	
Brightness	2.34	5.06	41.3	
Size-Hue	3.55	11.90	76.2	72.6
Size-Brightness	2.98	7.89	59.8	59.5
Hue-Brightness	3.76	13.55	84.2	
Size-Hue-Brightness	4.11	17.28	96.5	90.7

* Based upon error term for the analysis of variance, differences of .38 and .52 in I_t are significant at the .05 and the .01 level, respectively. I_t = Information transmitted in bits.

20. Fowler, F. D., D. B. Jones. *Target Acquisition Studies: (2) Target Acquisition Performance Color Vs. Monochrome TV Displays.* Martin Marietta Corporation, January 1972. (OR 11, p. 768.)

The authors investigated target acquisition on color and black-and-white TV using a terrain model and target silhouettes (buildings). They found that color did not generally improve detection or recognition range although some area x mode interactions were significant. (See Table 20.1.)

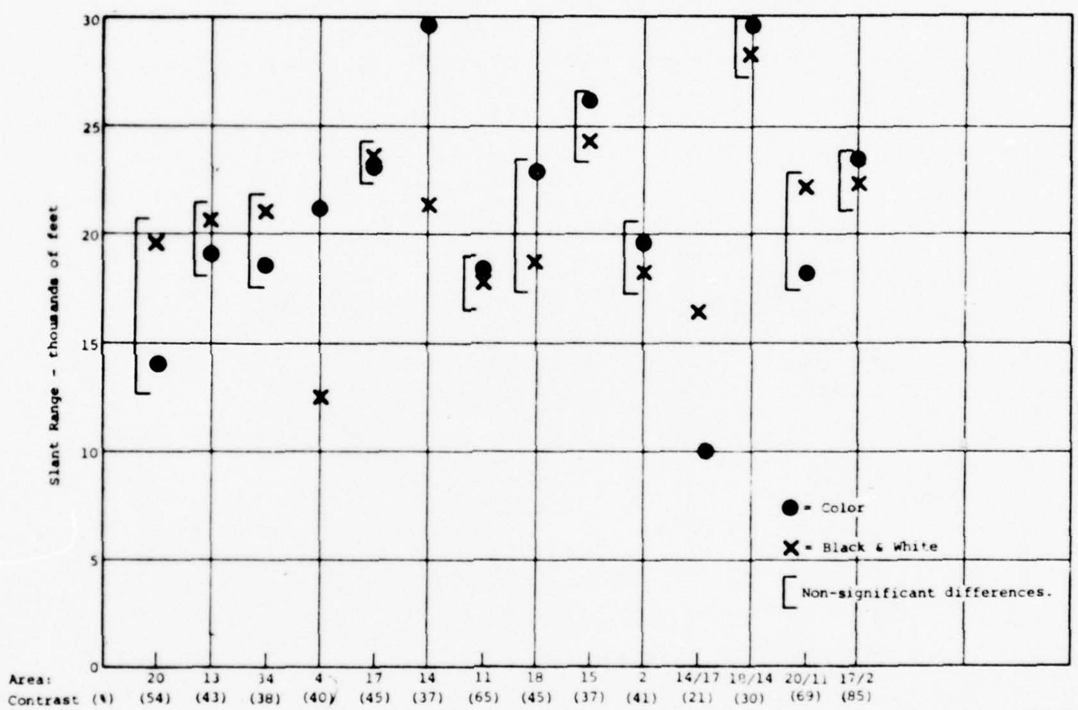
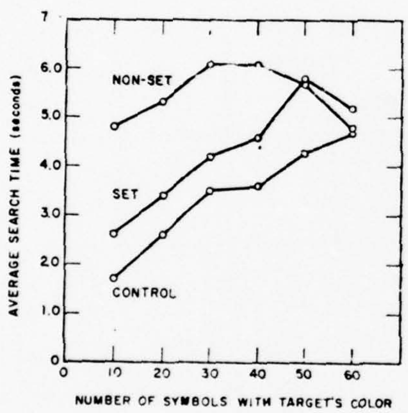


FIGURE 20.1. Detection Performance as a Function of Mode for Each Area.

21. Green, B. F., and Lois K. Anderson. "Color Coding in a Visual Search Task," *J. Exp. Psychol.*, Vol. 51 (1956), pp. 19–24.

The authors used red and green two-digit numbers in a search task under three conditions: Set varied the proportion of red to green numbers from 0 to 60 and S was told the number and color; non-set used the same conditions except S was not told the color; control used 10 to 60 numbers, all either red or green. They found that (1) when one color dominates (non-set) search times slightly decrease; (2) search time is approximately proportional to density (control), and (3) the presence of wrong color-coded symbols increases search times over single color codes (set vs. control). A second experiment was similar, but yellow and blue numbers were added with densities of 15, 30, 45, or 60 numbers of a single color for control. Set used 2, 3, or 4 colors of 15 numbers each. Non-set was the same as set except S was not told the color. They found that search time is less when numbers were blocked by color codes (set) than when all one color (control) or when S was not told color (non-set). When the color is known, it helps performance, but when it is not, adding color only hinders search time. (See Figures 21.1 and 21.2.)



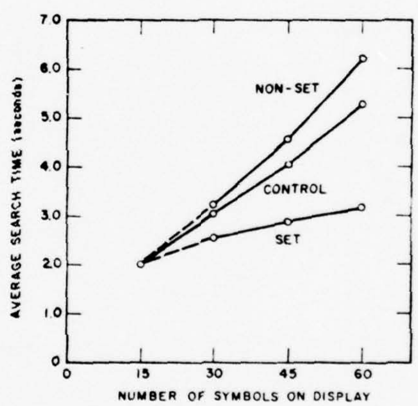


FIGURE 21.1. Average Search Time for Colored Numbers in Exp. I. Each point represents the geometric mean of 80 measurements. All non-set and set displays had 60 symbols; control displays had from 10 to 60 symbols, all of the same color.

FIGURE 21.2. Average Search Times for Colored Numbers in Exp. II. Each point represents the geometric mean of 240 measurements. Non-set and set displays had 15 symbols each of two, three, or four colors; all symbols on control displays had the same color.

22. Haines, R. F., L. Markham Dawson, Terye Galvan, and Lorrie M. Reid. *Response Time to Colored Stimuli in the Full Visual Field.* National Aeronautics and Space Administration, 1974 (NASA TN D-7927).

Reaction time (RT) was measured to round (45') colored (blue, yellow, green, red, and white) stimulii throughout the visual field. Red was seen at less than half the intensities of the other colors. They found that, out to 10^0 from the fovea, color naming performance was good for all colors. Performance deteriorated from 10^0 to 50^0 and dropped to chance levels beyond 50^0. Reaction time was fairly constant out to 30^0, with white providing the fastest, then yellow, red, green, and blue, the slowest RT (276, 288, 322, 323, and 341 msec). (See Figures 22.1 and 22.2; also Table 22.1.)

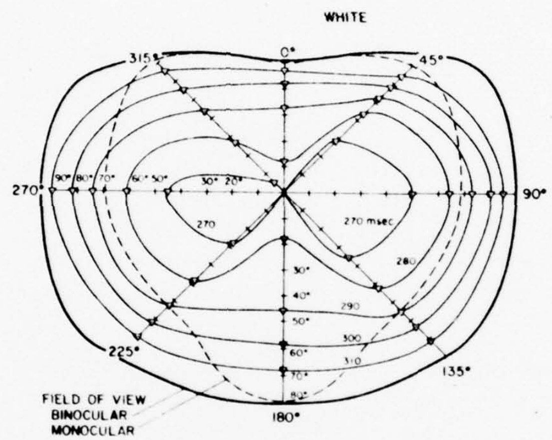


FIGURE 22.1. Retinal Iso-RT Zones for White.

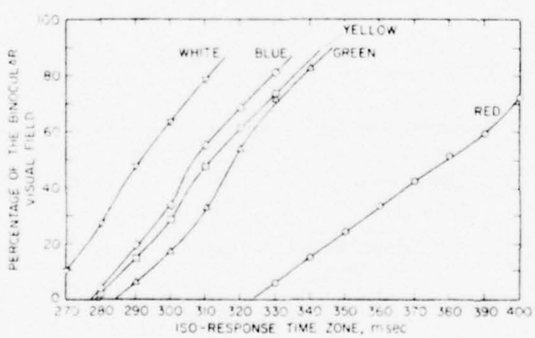


FIGURE 22.2. Percentage of the Binocular Visual Field Represented by the Iso-RT Zones Presented in Figure 22.1 for Each Color.

TABLE 22.1. Summary of RT Data for $\theta = 0^0$ Stimulus Position for Each Subject and Meridians.[a]

	Stimulus color				
	Blue	Yellow	Green	Red	White
Min. RT	331	279	301	313	269
Max. RT	353	301	343	330	286
Range	22	22	42	17	17
Mean RT	341	288	323	322	276
Mean S.D.	76.2	43	56.5	52.3	39.2
S.D./Range[b]	3.57	1.96	1.34	3.07	2.30

[a] All values in msec except as noted.
[b] Dimensionless value.

23. Hilgendorf, A. L., and John Milenski. *Effects of Color and Brightness Contrast on Target Acquisition. SEEKVAL Project 1A1.* Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio, AMRL, July 1974. (AMRL-TR-74-55.)

Target color and brightness contrast effects on direct vision detection of model tanks were investigated. They found that gray targets were easier to detect than green or brown ones and that negative contrast targets are harder to detect than positive ones (light on dark background). (See Figure 23.1.)

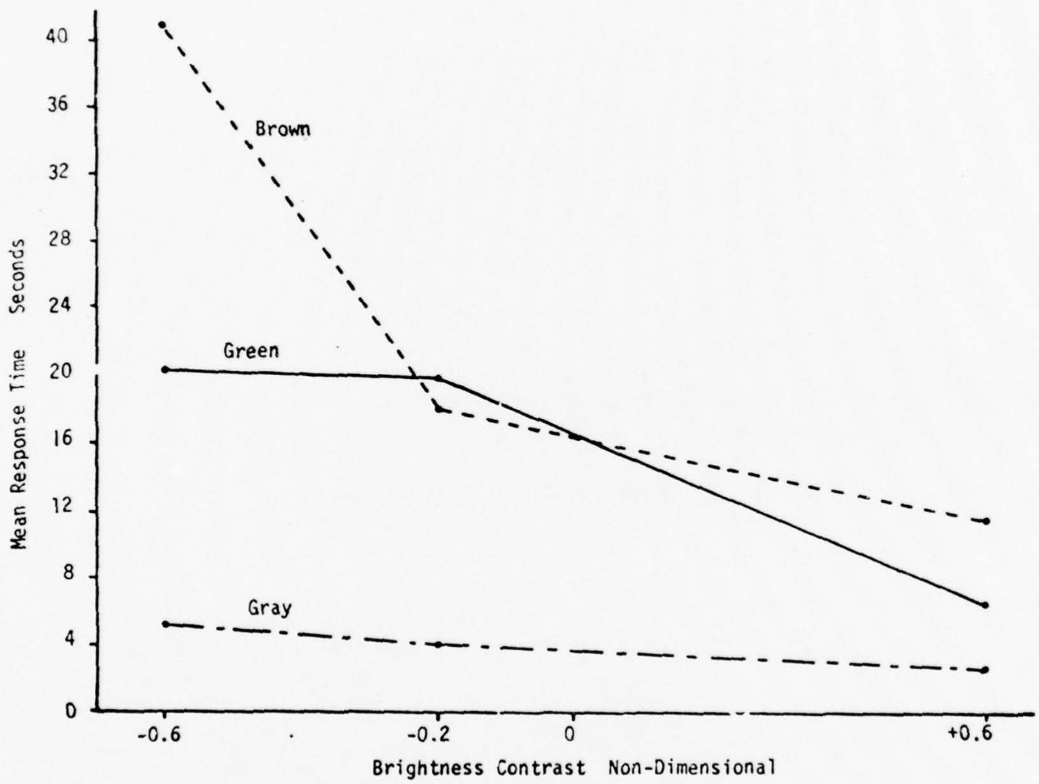


FIGURE 23.1. Unadjusted Color, Contrast Cell Mean Detection Response Times.

24. Hitt, W. D. "An Evaluation of Five Different Abstract Coding Methods," Exp. IV, *Hum. Factors*, Vol. 3 (1961), pp. 120–130.

Hitt investigated the relative effectiveness of five coding methods (numbers, letters, geometric shapes, colors, and configuration–i.e., small square placement in relation to large square) on five tasks (identification, location, count, compare, and verify) while varying target density (40, 80, and 120 per display) and code levels 2, 4, or 8). He found that (1) identification and search are different tasks; (2) numbers were better for identifying, while color was better (i.e., correct responses per minute) for locating, and no significant difference between the two were found for the remaining tasks; and (3) performance decreased with more code levels and greater densities. (See Tables 24.1 through 24.3.)

TABLE 24.1. The Effect of Coding Methods on Operator Tasks.

Tasks	*Rank order of code categories*				
	First	*Second*	*Third*	*Fourth*	*Fifth*
Identify	Numeral 13.64	Letter 13.02	Shape 12.53	Color 12.34	Configuration 11.77
Locate	Color 8.46	Numeral 7.42	Letter 7.25	Shape 6.94	Configuration 4.03
Count	Numeral 12.60	Color 12.22	Shape 11.49	Letter 11.11	Configuration 7.07
Compare	Numeral 6.85	Color 6.72	Shape 6.56	Letter 6.33	Configuration 4.76
Verify	Numeral 10.01	Color 9.95	Shape 9.50	Letter 9.05	Configuration 6.60

Note:

(1) Scores reported in terms of mean correct response per minute.
(2) Code categories connected by line are not significantly different at $p < 0.05$.

TABLE 24.2. Effect of Number of Code Levels on Operator Performance.

Number of code levels	*Mean number of correct responses per minute*
2	10.31
4	8.76
8	8.34

TABLE 24.3. Effect of Target Density on Operator Performance.

Target density (Number of symbols per display)	*Mean number of correct responses per minute*
40	11.36
80	8.45
120	7.60

25. Jameson, Dorothea, and L. M. Hurvich. "Perceived Color and Its Dependence on Focal, Surrounding, and Preceding Stimulus Variables," *Opt. Soc. Amer., J.*, Vol. 49 (1959), pp. 890–898.

The authors mathematically postulate that color perception can be more accurately defined by including surround and preceding stimulus variables in addition to the conventional hue, saturation, and brightness considerations. They then, experimentally, varied target and background color and target size, keeping surround size (37^0) constant. Subjects perceived target colors, in the region of the background color, to be less saturated than they were. Changes in surround luminance resulted in changes in perceived hue and brightness. Target-background hues of the same color tend to desaturate the target or change it to surround complement. (See Figure 25.1.)

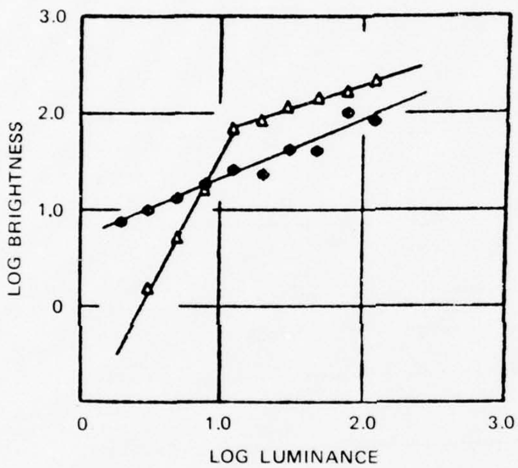


FIGURE 25.1. Brightness Scales. Test stimuli: 650 mμ. Chromaticity coordinates of surround stimulus: x = 0.71, y = 0.29. Circles with vertical bars: surround luminance = 3 mL. Triangles: surround luminance = 30 mL. See text.

26. Jeffrey, T. E., and F. J. Beck. *Intelligence Information From Total Optical Color Imagery*. U.S. Army Behavior and Systems Research Laboratory, Arlington, Va., November 1972. (Research Memorandum 72-4.)

This study compared image interpreter performance using three types of 35-mm slides: conventional black-and-white, Ektachrome color, and black-and-white slides viewed through a special viewer (total optical color) which provided color imagery of the achromatic slide. They found that subjects could extract the required information faster with both color conditions (89.2 sec, Ektachrome; 87.2 sec, TOC viewer) than with the achromatic condition (106.4 sec). The time was significant for color vs. achromatic.

27. Jones, M. R. "Color Coding," *Hum. Factors*, Vol. 4 (1962), pp. 355–365.

Jones conducted a literature search on color-coding covering 1941 to 1961. The author found that color works well as an attention-getting code with search tasks and that luminous color-coding (i.e., CRT) studies with complex displays are needed. A rather wordy review, but provides a good reference source for color-coding work.

28. Kanarick, Arnold F., and Ronald C. Petersen. "Redundant Color Coding and Keeping-Track Performance," *Hum. Factors*, Vol. 13 (1971), pp. 183–188.

The authors investigated redundant vs. numbers or colors in a keeping-track task. They found that the redundant coding did not aid performance. The best performance was found to be associated with the high-value channels (the Ss were told certain channels were worth more than others) regardless of coding conditions. (See Figure 28.1.)

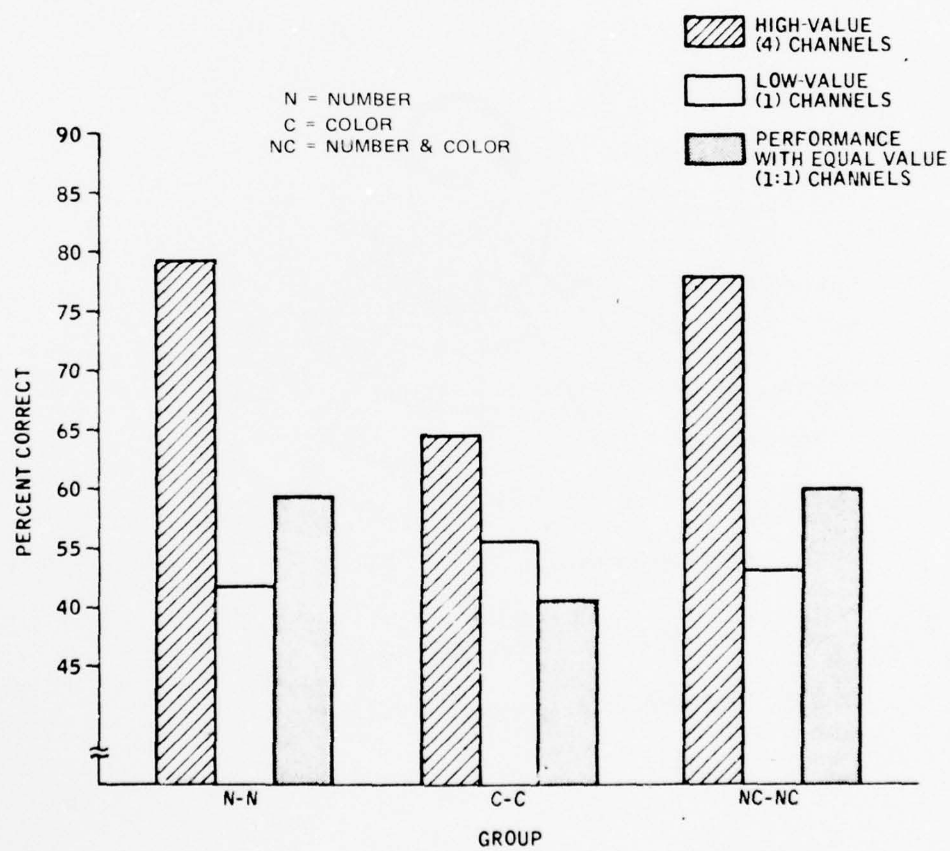


FIGURE 28.1. Percent Correct Responses as a Function of Homogeneous Coding Groups for the Channel Value Conditions.

29. Kennedy, M. L., J. A. Schmacker, L. F. Hanes, and M. L. Ritchie. *Technology for Information Presentation. Part IV. Color Coding.* U.S. Air Force, 1963. (USAF ASD Tech. Report No. 63-000.)

These authors present their information on color coding (as of 1963) in four sections: (1) A literature review of experimental and design literature applicable specifically to aircraft cockpit uses. (2) The use of color in existing cockpits and developmental efforts involving color-coded displays. (3) A guide for the selection of an appropriate code and, given that color coding is chosen, color-coding criteria are presented. (4) The uses of color in three display concepts are discussed and evaluated. Their final proposal is that color be used in a "scan-lighting" scheme whereby conventional instrument display arrangements be augmented by bezel or backlighting in color specific displays associated with a particular phase of a mission. (See Figures 29.1 and 29.2.)

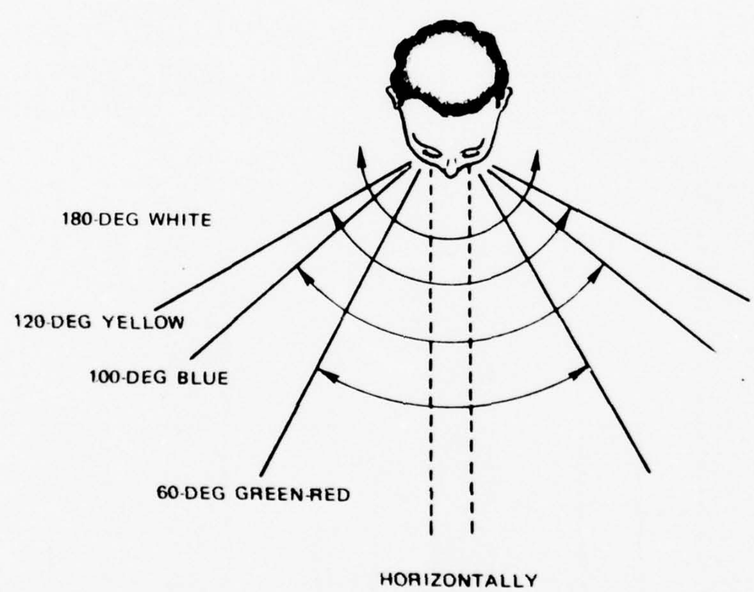


FIGURE 29.1. Horizontal Angular Color Limits (After Lopatin, et al).

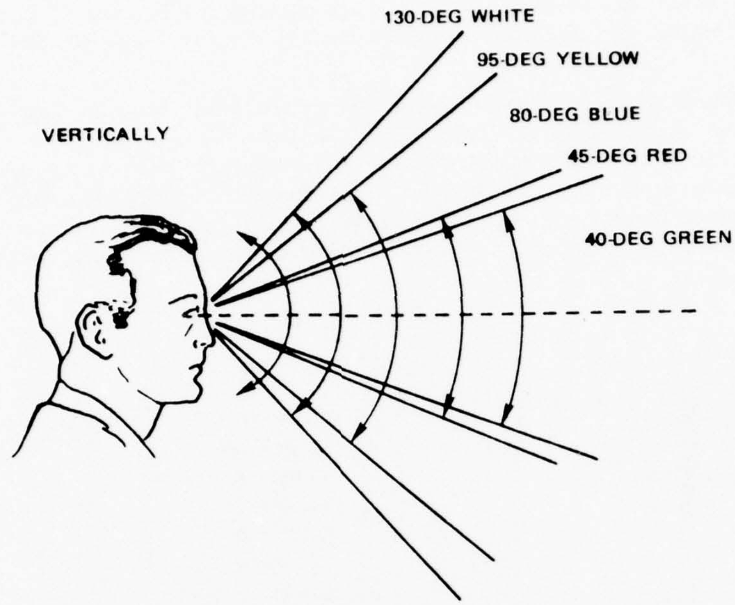


FIGURE 29.2. Vertical Angular Color Limits (After Lopatin, *et al*).

30. Lit, A., R. H. Young, and M. Shaffer. "Simple Reaction Time as a Function of Luminance for Various Wave Lengths," *Perception and Psychophysics*, Vol. 10 (1971), pp. 397–399.

The authors measured reaction time to white, red, yellow, green, and blue light over a wide range of retinal illuminances. They found that reaction time for all colors (and white) systematically deteriorates with decreasing illumination through the photopic range. However, at the transition point from photopic to scotopic vision (about -1.0 log td), the shorter wavelength lights are displayed laterally with lesser illuminace. This suggests that rods are more sensitive to the shorter wavelengths of light, while cones sense little distinction in stimulus wavelength. (See Figure 30.1.)

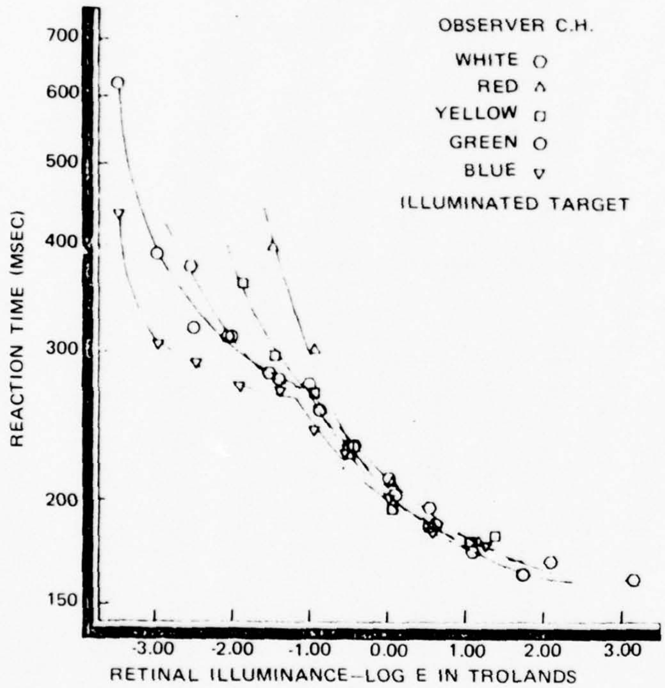


FIGURE 30.1. Average Median Reaction Time (Milliseconds) on a Log Scale Plotted as a Function of Retinal Illuminance of the White Light (log td) for Subject C.H.

31. Markoff, J. I. *Target Recognition Performance With Chromatic and Achromatic Displays.* Honeywell, Inc. SRM-148, January 1972.

Resolution, target size, ambient illumination, and chroma were investigated to determine their effects upon target recognition performance. Ambient illumination had no effect on performance. Color targets were recognized faster with fewer errors than were black-and-white counterparts. Resolution degraded performance with the black-and-white photographs more than it did with the color ones, especially at the lower resolution levels. The soldier was easier to recognize than either tanks or jeeps. The soldier was easier to recognize than either tanks or jeeps. The larger the targets, the easier to recognize. The major finding was that, with luminance contrast held constant, color photographs provided faster response times with fewer errors than did black-and-white photos of the same scene. (See Table 31.1.)

TABLE 31.1. Scheffé Test on Correct Response Time.

Factor B - Image Chroma Degrees of Freedom = 1, 1008	
Means	
B-W	Color
5.95	3.37
Levels	F-Ratio
1 vs 2	108.745**

Factor C - Resolution Degrees of Freedom = 1, 1008			
Means			
R1	R2	R3	R4
1.93	4.43	6.03	6.24

Levels	F-Ratio
1 vs 2	51.385**
1 vs 3	138.150**
1 vs 4	152.233**
2 vs 3	21.026**
2 vs 4	26.728**
3 vs 4	0.342

Factor D - Target Type Degrees of Freedom = 1, 1008		
Means		
Tank	Jeep	Soldier
4.49	5.12	4.07

Levels	F-Ratio
1 vs 2	1.179
1 vs 3	5.649**
2 vs 3	11.990**

Factor E - Target Size Degrees of Freedom = 1, 1008		
Means		
Small	Medium	Large
6.25	4.92	2.80

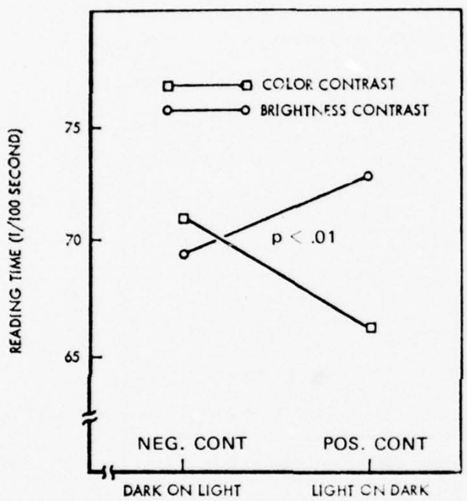
Levels	F-Ratio
1 vs 2	19.408**
1 vs 3	130.651
2 vs 3	49.348**

**$p < 0.01$.

[a] R1 was the resolution level when the image was in sharp focus. The remaining levels were defocused 0.1, 0.15, and 0.20 inches (R2, R3, and R4, respectively). The study provides the resulting MTF curves.

32. McLean, M. V. "Brightness Contrast, Color Contrast and Legibility," *Hum. Factors*, Vol. 7 (1965), pp. 521–526.

McLean investigated the effects of adding color contrast to brightness contrast, positive and negative contrast, and several luminance contrast values (15, 20, 25, 33, 41, 49 percent) on a speed-of-reading-dial task with pilots and non-pilots. He found: (1) adding color contrast provided faster reading time than did achromatic contrast alone (0.69 versus 0.71 sec); (2) 15% contrast produced slower speeds than did the other values; and (3) color is better for positive (light on dark) contrast with the reverse true for luminance contrast (dark on light better). (See Figures 32.1 and 32.2.)



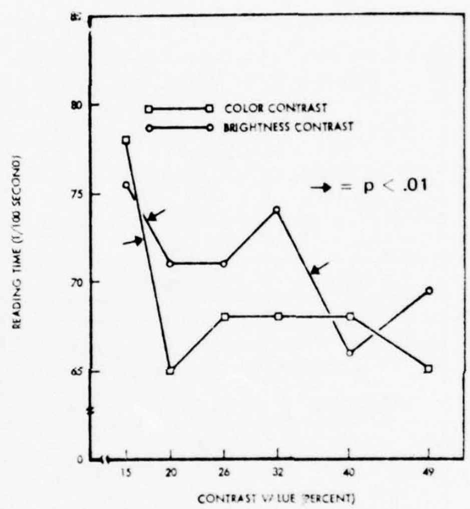


FIGURE 32.1. The Effects of the Interaction Between Color and Brightness Contrast With Direction of Contrast on Reading Time.

FIGURE 32.2. The Effects of Low to High Contrast Value on Reading Time.

33. Meister, D., and D. J. Sullivan. *Guide to Human Engineering Design for Visual Displays*. Bunker-Ramo Corporation, Canoga Park, Calif., August 1969.

A design guide for visual displays, this document contains excellent sections on TV and color-coding considerations. The salient research up to 1969 is presented in easily understood graphs which provide the designer with the best available human factors data. Longer wavelength colors are more accurately read than shorter ones. (See Figure 33.1.)

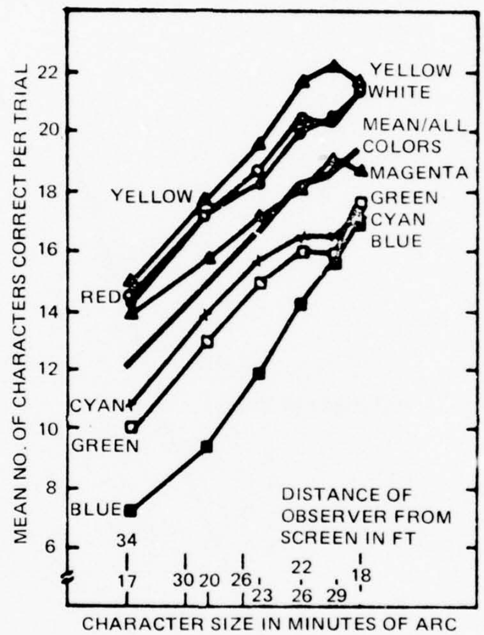


FIGURE 33.1. Subject Performance in Reading Color-Coded Alphanumerics as a Function of Size and Color.

34. Muller, P. F., Jr., R. C. Sidorsky, A. J. Slivinske, and P. M. Fitts. *The Symbolic Coding of Information on Cathode Ray Tubes and Similar Displays.* Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, WADC, 1955. (USAF WADC Tech. Rep. 55-375.)

Eleven experiments were conducted which deal with four basic codes (inclination, ellipse ratio, blip diameter, and color). The report contains one section dealing with recommendations for design engineers and a second section describing the experiments. Two of the experiments dealt with color compared to inclination coding. While the authors found inclination coding to be the most promising of the four codes investigated, performance with color was as good and, in some cases better, than inclination coding in the two experiments reported. (See Figure 34.1.)

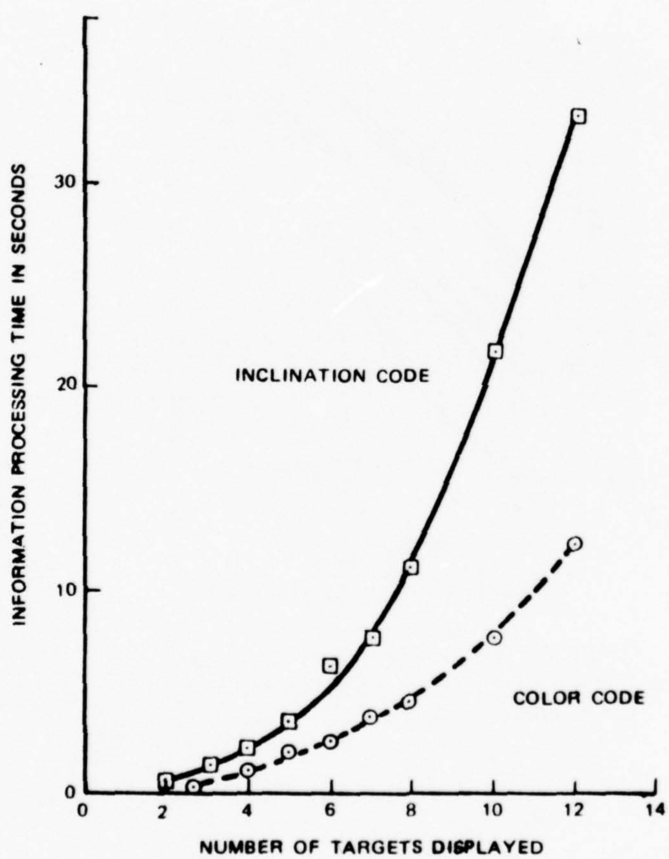


FIGURE 34.1. Information Processing Time as a Function of Number of Targets Displayed for the Inclination and Color Codes of Exp. IX. Each target was one of 12 symbols and the task was to report as conflicts any two or more targets that were similarly coded.

35. Newman, K. M., and A. K. Davis. *Multidimensional Nonredundant Encoding of a Visual Symbolic Display.* U.S. Navy Electronics Laboratory Center, San Diego, Calif., NELC, July 1961. (NELC/Report 1048.)

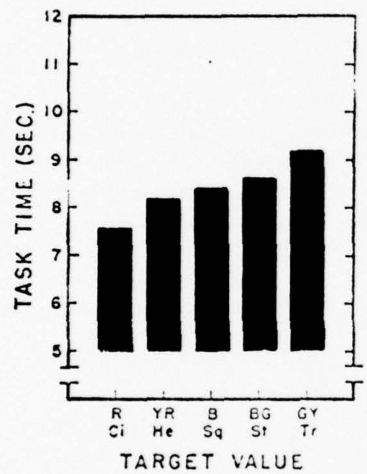
Geometric symbols, alone and in one or more combinations with brightness (bright and dim), flashing rates (steady, 2/4 per sec), and colors (white, red, green, and yellow), were evaluated in terms of response time and errors. The tasks were to: (1) match a stimulus signal with one of 36 possible alternatives; (2) call out the symbol meaning; (3) detect stimulus from among 18 overlapping pairs; and (4) call out meaning (decode). The results show that a symbol in combination with two or three colors provided the fastest response times, while combinations involving all levels provided the slowest response times, with multiple flashing rates degrading performance more than other coding methods. Similar results were found for error rates. Color coding provided the fastest response times and the fewest errors compared to the other codes.

36. Payne, M. C., Jr. "Color as an Independent Variable in Perceptual Research," *Psychol. Bull.*, Vol. 61 (1964), pp. 199–208.

Payne reviewed the literature concerned with the effect of color on perceived distance, size, weight, temperature, and visual acuity. He suggests that luminance is the major cue for distance, size, and weight, since brighter objects appear larger, nearer, and lighter than darker objects, regardless of hue. Hue is more important for apparent temperature (green and blue coolest, white intermediate, yellow and amber warmest). For static visual acuity, longer wavelengths are better than shorter wavelengths under colored illumination. Colored targets on dark backgrounds are better than corresponding achromatic targets. Colors of 500–600 nm are better than extremes. Yellow on a dark background is especially good.

37. Promisel, D. M. "Visual Target Location as a Function of Number and Kind of Competing Signals," *J. Appl. Psych.*, Vol. 45 (1961), pp. 420–427.

Promisel discusses the meaning of redundant, nonredundant, and partially redundant coding methods introductory to a study of the effects of multicoded signals (hue and geometric shape) on 40 total-target to nontarget signals (0,2,4,6,8), competing signals (0,8,16,24,32 signals identical in one dimension, but not both), competition distribution (half hue, half shape, or all hue), and five multicode values (red circle, blue square, etc.) measured as a function of time and errors. He found that: (1) Red circles were found fastest with fewest errors. (2) Search time increased almost linearly with increasing number of targets (as do errors) and with increasing number of competing signals. (3) He argues—rather circuitously and unconvincingly—that hue has a greater effect on variations in search time than does shape. (4) Multicodes provided slightly better times than a partially redundant coding method. (See Figure 37.1 and 37.2.)



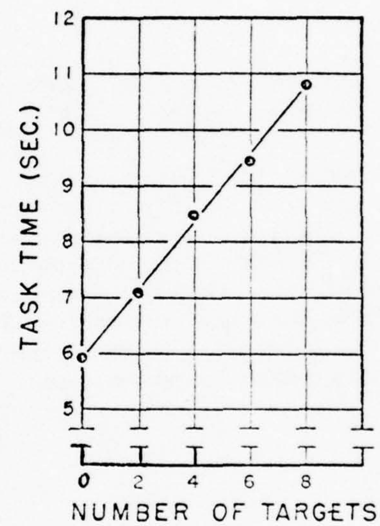


FIGURE 37.1. Time To Locate Different Hue-Shape Combinations, Averaged Over All Experimental Conditions.

FIGURE 37.2 Average Time To Locate All the Target Signals as a Function of the Number of Target Signals. (Each point is the average for all other experimental conditions.)

38. Reynolds, H. N. "The Visual Effects of Exposure to Electroluminescent Instrument Lighting," *Hum. Factors*, Vol. 13 (1971), pp. 29–40.

Reynolds describes two studies on the effects of electroluminescent (EL) white and green cockpit instrument panel lighting compared with incandescent red (aviation red) on scotopic absolute and acuity thresholds, and EL white, green, and yellow with aviation red light for transilluminated letter legibility. He found that: (1) Absolute and acuity thresholds were better after exposure to red light than to white or green light. Green lighting raised acuity threshold more than other colors and is estimated to take about 3 minutes for readaptation compared to

1 minute for red light. (2) There was no effect of light color on better legibility except for the largest letter size (48.3 min) where slightly more luminance was required to differentiate red-lighted letters. Generally, smaller letters required greater luminance for reading. (See Table 28.1 and Figure 38.1.)

TABLE 38.1. Scotopic Acuity Thresholds Following Exposure to Three Colors of Instrument Lighting at 0.05 ftL.

	Scotopic Acuity Threshold				
		Ft.-L × 10^{-4}		*Increase in Threshold*	
Condition	*Log ft.-L.*	*Mean*	*σ*	*Log ft.-L.*	*%*
Dark Adapted	$\bar{4}$.5960	3.95	2.66	–	–
Red Incandescent	$\bar{4}$.6690	4.67	2.25	+0.0730	18.2
White Electroluminescent	$\bar{4}$.8654	7.34	4.15	+0.2694	85.8
Green Electroluminescent	$\bar{3}$.0047	10.11	5.94	+0.4087	155.9

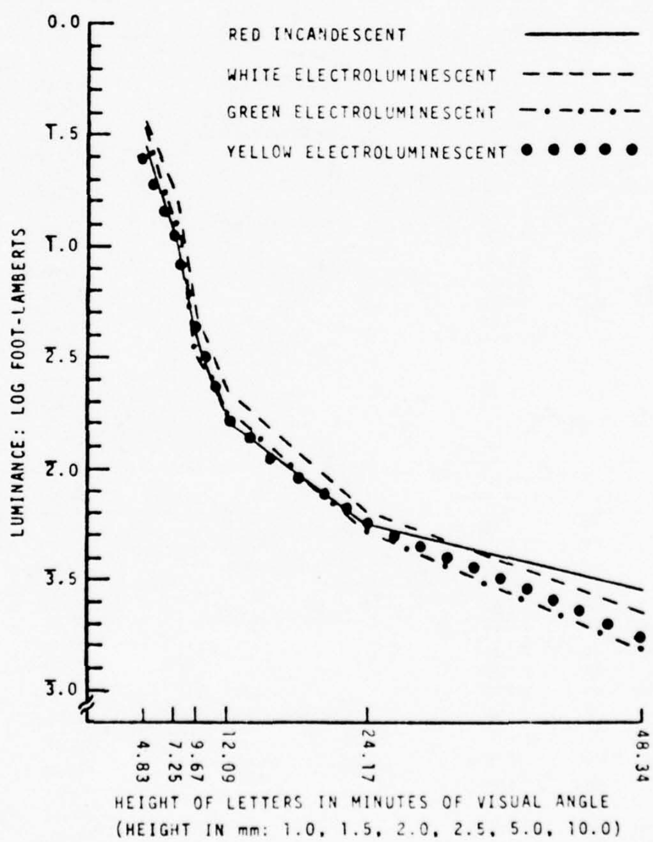


FIGURE 38.1. Mean Luminances Required for Legibility of Letters With Four Colors of Lighting.

39. Reynolds, R. E., R. M. White, Jr., and R. L. Hilgendorf. "Detection and Recognition of Colored Signal Lights," *Hum. Factors*, Vol. 14 (1972), pp. 227–236.

Two experiments were conducted to investigate the conspicuousness of red, green, yellow, and white lights seen against copper, tan, blue, and green backgrounds measured by detection speed and identification accuracy under high and low ambient illumination with male and female Ss. (High and low illumination were defined in terms of reflected luminance from the four backgrounds, which were green–27, blue–6, tan–3, and copper–1 candela per square meter for the bright condition and all less than 0.3 cd/m^2 for the dim one. A cd/m^2—or nit—is equivalent to 0.292 ftL.) Thus, background luminance varied from 7.9 to 0.29 ftL. They found that red, then green, yellow, and white, in that order provided the best response times. The fewest errors were with green signals (4.2%) while yellow provided the most (43.8%). Background color did not significantly affect response time. Under bright light, more errors and time resulted. Females were faster and had fewer errors. (See Tables 39.1–39.4.)

TABLE 39.1. Mean Reaction Times for Individual Responses in Experiment 1.

Factor	*Group*	N	*Time (Sec.)*
Overall		48	2.821
Sex of Subject	Female	24	2.662
	Male	24	2.979
Background Color	Blue	12	2.663
	Copper	12	2.687
	Tan	12	2.810
	Green	12	3.123
Ambient Illumination	Dim	48	1.313
	Bright	48	4.328
Stimulus Color	Red	48	2.019
	Green	48	2.341
	Yellow	48	2.992
	White	48	3.930

TABLE 39.2. Percent Error in Color Naming in Experiment 1.

Factor	*Group*	N	*% Error*
Overall		48	20.17
Sex of Subject	Female	24	17.53
	Male	24	22.80
Background Color	Blue	12	17.59
	Copper	12	17.71
	Tan	12	22.22
	Green	12	23.14
Ambient Illumination	Dim	48	12.68
	Bright	48	27.67
Stimulus Color	Green	48	4.17
	Red	48	8.33
	White	48	24.42
	Yellow	48	43.75

TABLE 39.3. Mean Reaction Times for Individual Responses in Experiment 2.

Factor	*Group*	N	*Time (Sec.)*
Overall		96	2.204
Identification	No	48	2.073
	Yes	48	2.335
Sex of Subject	Male	48	2.142
	Female	48	2.266
Background Color	Green	24	2.141
	Blue	24	2.199
	Copper	24	2.228
	Tan	24	2.250
Ambient Illumination	Dim	96	1.164
	Bright	96	3.245
Stimulus Color	Red	96	1.785
	Green	96	1.991
	Yellow	96	2.350
	White	96	2.691

TABLE 39.4. Percent Error in Color Naming in Experiment 2.

Factor	*Group*	N	*% Error*
Overall		48	17.39
Sex of Subject	Female	24	16.67
	Male	24	18.11
Background Color	Blue	12	14.93
	Green	12	16.32
	Copper	12	18.28
	Tan	12	20.02
Ambient Illumination	Dim	48	11.40
	Bright	48	23.38
Stimulus Color	Green	48	4.28
	Red	48	6.13
	White	48	27.67
	Yellow	48	31.48

40. Rizy, E. F. *Color Specification for Additive Color Group Displays.* Rome Air Development Center, Research and Technology Division, Air Force Systems Command, Griffiss Air Force Base, New York, August 1965. (RADC-TR-65-278, AD 621 068.)

Rizy investigated the effects of additively mixing red, green, and blue primaries to arrive at a seven-color code producing the most discriminable and legible alphanumerics for a group-viewable projected display. The generated symbol colors were: red, green, blue, yellow, magneta, cyan, and white. He found that filter pairs of 516/595 and 516/581 nm produced the best performance as did symbol colors red and yellow, with green providing the worst performance. (See Figure 40.1.)

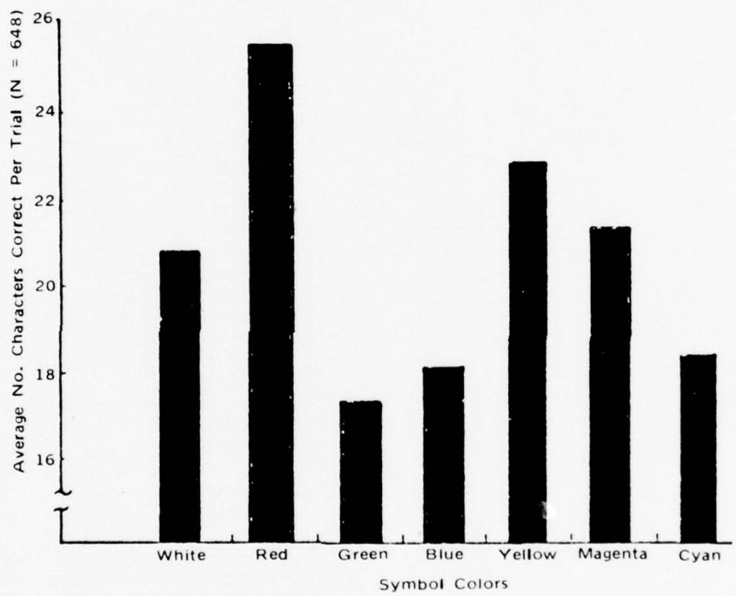


FIGURE 40.1. Subject Performance for Symbol Colors Averaged Over All Conditions.

41. Rusis, G. *The Utility of Color in Visual Displays.* Autometics, Anaheim, Calif., August 1966. (T6-1570/3111.)

The report consists of a review of color-coding literature emphasizing applications. It contains sections on colorimetry, display technology, and human factors considerations. It was found that red and yellow are the most efficient color codes, although additional colors (6 surface to 9 lights) can be used with high accuracy. Primary trade-offs may be brightness/contrast, resolution, persistence, etc. (See Table 41.1.)

TABLE 41.1. Comparison of Coding Techniques.

Code Dimension	Number Code Steps	Evaluation	
Color	11	good	Objects of a given color quickly and easily identified in a field of various colored objects. Little space required.
Numerals & letters	Unlimited	good	Number of coding steps unlimited. Requires little space if there is good contrast and resolution.
Geometric Figures	15 or more	good	Certain geometric shapes are easily recognized. Little space required if resolution is good.
Area	5	fair	Requires considerable space on display.
Visual Number	6	fair	Requires considerable space on display.
Length	4-5	fair	Limited number of usable code steps. Will clutter a display with many signals.
Angular Orientation	12	fair	95% of the estimates will be in error by less than 15°
Brightness	3-4	poor	Limited number of usable code steps. Poor contrast effects will reduce visibility of weaker signals. Fatiguing.
Flash Rates	5	poor	Distracting and fatiguing. Interacts poorly with other codes.
Stereoscopic Depth	?	fair	Realistic method of coding range or altitude. Requires complex electronic displays.

42. Saenz, Norman E., and Charles V. Riche, Jr. "Shape and Color as Dimensions of a Visual Redundant Code," *Hum. Factors*, Vol. 16 (1974), pp. 307–312.

The authors investigated the effect four geometric shapes, four colors, and four redundant color-shape coded targets have on a timed search and detect task. The background contained clutter objects consisting of irrelevant shapes and/or colors. The authors found the redundant and the color code to be more effective than the shape code. Ordered by search time, from best to worst, for the color redundant code the results were: yellow, blue, red and green. For shapes the order was circle, square, cross, and triangle. (See Table 42.1 and 42.2.)

TABLE 42.1. Mean Log Search Times (Seconds) for Codes by Shapes, for Codes, and for Shapes.

	Shapes				
Codes	*Circle*	*Square*	*Cross*	*Triangle*	*Codes*
Color	.792	.789	.799	.790	.792
Shape	.853	.876	.899	.968	.899
Redundant	.726	.735	.748	.755	.741
Shapes	.790	.800	.815	.837	

TABLE 42.2. Mean Log Search Times (Seconds) for Codes by Color and for Color.

	Colors			
Codes	*Yellow*	*Red*	*Blue*	*Green*
Color	.707	.771	.793	.899
Shape	.946	.883	.897	.871
Redundant	.704	.744	.738	.778
Colors	.786	.799	.809	.849

43. Shontz, William D., Gerald A. Trumm, and Leon G. Williams. "Color Coding Information Location," *Hum. Factors*, Vol. 13 (1971), pp. 237–246.

The authors investigated partially redundant color coding, achromatic coding, and uncoded color for information location on aeronautical charts. They found that coding reduced search time over uncoded maps. Additionally, no significant difference was found between achromatic and color-coded search times. (See Figure 43.1.)

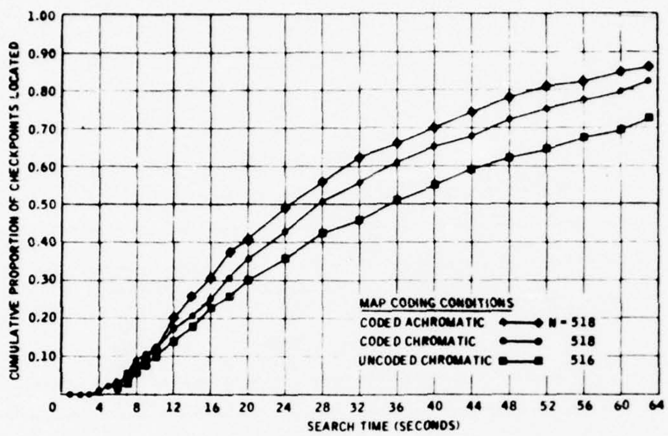
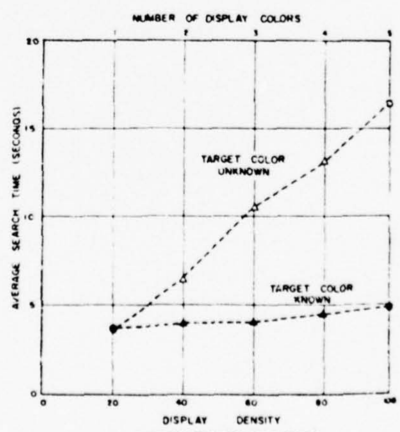


FIGURE 43.1. Search Time Distributions for Coding Conditions.

44. Smith, S. L. "Color Coding in Visual Search," *J. Exp. Psych.*, Vol. 64 (1962), pp. 434–440.

Smith investigated target density, number, and color, known or unknown, against a white or black background as a function of search time. He found that knowledge of target color, density and number were significant; neither target color (red, green, blue, orange, and black/white) nor background were significant. (See Figure 44.1.)

FIGURE 44.1. Search Time as a Function of Display Density When Target Color Is Known and Unknown and When There are 20 Items of Target Color in all Cases.



45. Smith, S. L. "Color Coding and Visual Separability in Information Displays," *J. Appl. Psych.*, Vol. 47 (1963), pp. 358–364.

Smith studied five item codes (letter, 3-digits, and vector-arrow) in white on black or 1 of 5 colors (red, yellow, green, blue, or white) and varied density (20, 60, or 100 codes) as a function of search and counting tasks. For the color condition, a color was used with a letter representing a redundant coding technique. He found that both search time and errors increased with density. The redundant color code reduced search time (65%), counting time (69%), and counting errors (76%). Target color was not significant. (See Figure 45.1.)

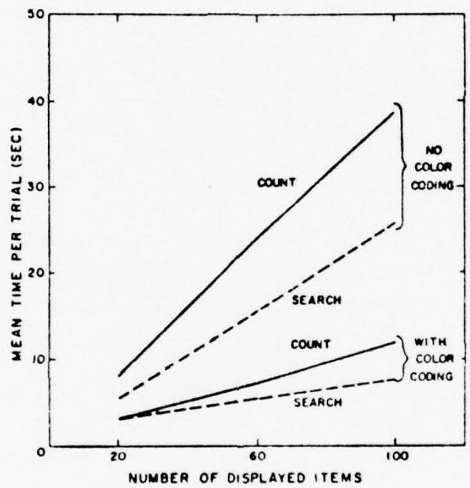


FIGURE 45.1. Average Counting and Search Times as a Function of Display Density With and Without Color Coding.

46. Smith, S. L., and D. W. Thomas. "Color Versus Shape Coding in Information Displays," *J. Appl. Psych.*, Vol. 48 (1964), pp. 137–146.

The authors investigated color compared to shape coding of symbols on a rear projection display. They varied density (20, 60, or 100 symbols) color (red, yellow, green, blue, and white), symbols (military shapes, geometric shapes, and aircraft shapes–five of each kind) and three coding schemes (color irrelevent–form discrimination, color constant–the same for all

targets, and color varied–military shape constant) in a counting task measuring accuracy and errors. They found: (1) counting time increased linearly with increased density, as did errors; (2) colors were counted at least twice as fast as the next best code–military symbols; (3) red, yellow, and white were counted equally fast, while blue was more difficult and green took the longest; and (4) some shapes were counted faster than others with ships, stars, and B-52s easier than radars, triangles, and C-54s. (See Figures 46.1 through 46.3.)

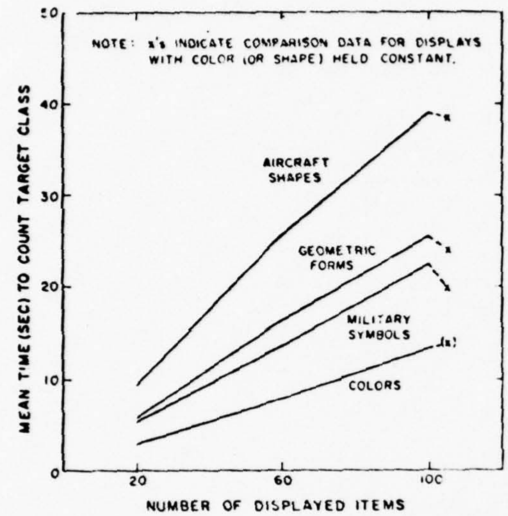


FIGURE 46.1. Average Counting Time as a Function of Display Density, Comparing Color Coding With the Three Shape Codes.

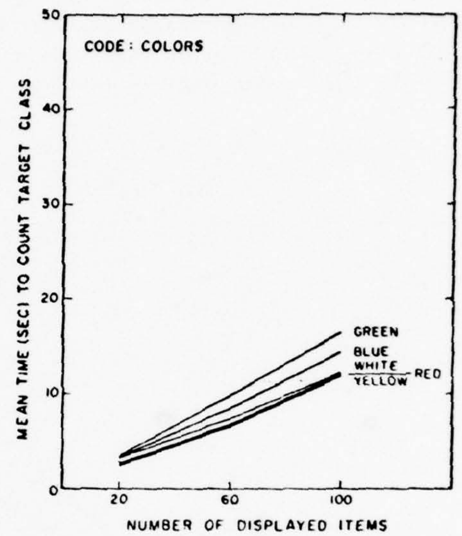


FIGURE 46.2. Average Counting Time as a Function of Display Density, Comparing Different Color Target Classes.

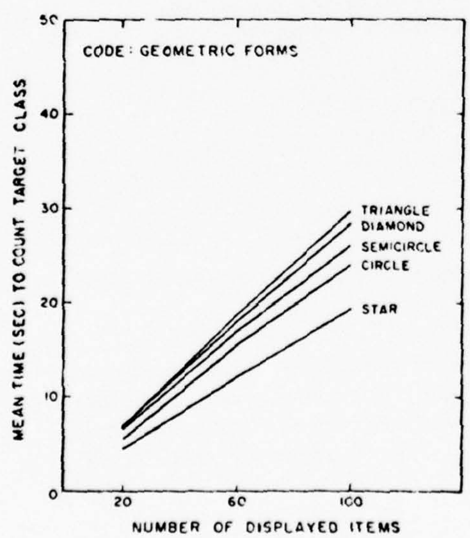
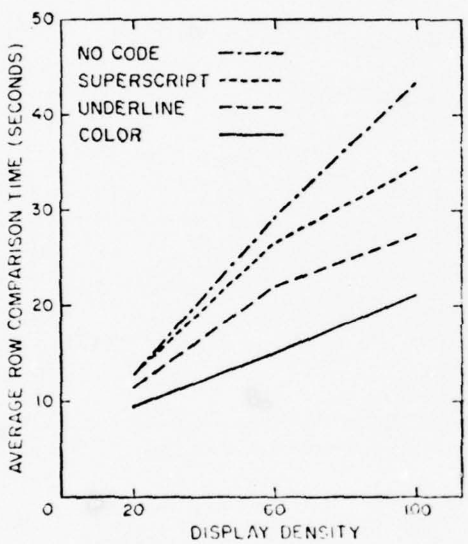


FIGURE 46.3. Average Counting Time as a Function of Display Density, Comparing Different Geometric Form Target Classes.

47. Smith, S. L., Barbara B. Farquhar, and D. W. Thomas. "Color Coding in Formatted Displays," *J. Appl. Psych.*, Vol. 49 (1965), pp. 393–398.

The authors studied the effects of color, superscript, and underline coding on add-up-the-row and counting tasks providing time and error measures, for both redundant coding and competing stimuli. They found that: (1) comparison time increases with increasing display density; (2) comparison was easier for lower numbers than higher ones; (3) widely disparate numbers were easier to compare than similar numbers; (4) color-coded numbers decrease both time and errors over uncoded ones; (5) color was a superior coding technique for both comparison and counting tasks; and (6) color was relatively more effective in a counting than in a comparison task for formatted displays. A formatted display, as used here, is organized by row and column structure as opposed to random target placement. (See Figures 47.1 and 47.2.)



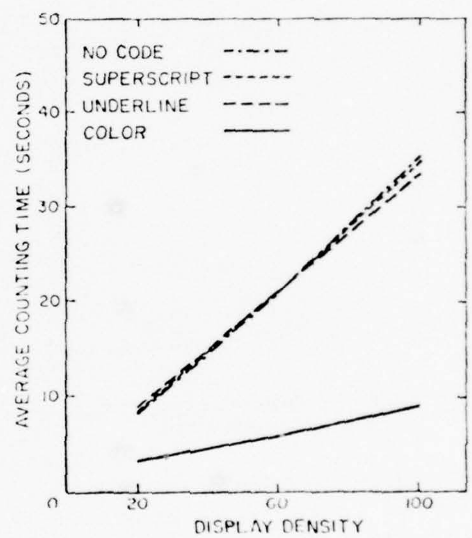


FIGURE 47.1. Average Row-Comparison Time as a Function of Display Density for Relevant Item Coding.

FIGURE 47.2. Average Counting Time as a Function of Display Density for Relevant Item Coding.

48. Tickner, A. H. and E. C. Poulton. "Watching for People and Actions." *Ergonomics*, Vol. 18 (1975), pp. 35–51.

A color and black-and-white film of a street scene was observed by subjects for 1, 2, or 4 hours. Their task was to watch for suspects (whose still photographs were in color or black-and-white) and suspicious behavior. They found that suspects were detected more often with color than with black-and-white film, especially when the session was preceded by a short color film (20 seconds) of the suspect. It is possible that a short black-and-white film would also improve performance, although this condition was not tested. The authors note that color photos with color film were not advantageous over black-and-white photos with color film.

49. Tyte, R., J. Wharf, and B. Ellis. "Visual Response Times in High Ambient Illumination," *Society for Information Display Digest*, 1975, pp. 98–99.

The authors investigated response time as a function of target color and luminance under bright (10^5 lux) illumination. The targets were spots of light subtending 10.7 . Their results show that response time decreases with increasing luminance. A leveling trend occurs at about 5 ftL and continues out to the tested maximum of 137 ftL (470 nits). Response time was also found to be differentially affected by stimulus wavelength and luminance, with red providing faster response times at lower luminances than either green or yellow. These findings are in only partial agreement with Lit, et al. The authors speculate that these findings indicate the eye perceives contrast in each color channel independently of overall brightness (See Figures 49.1 through 49.3.)

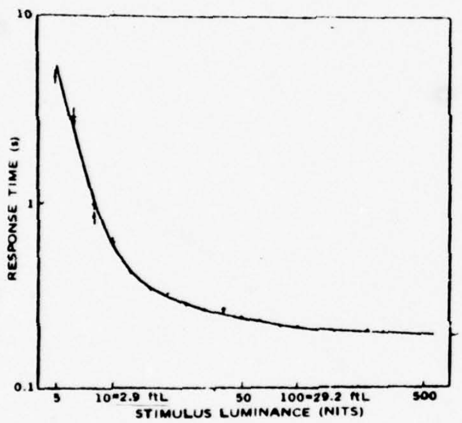


FIGURE 49.1. Subject's Response Time as a Function of Stimulus Luminance in Nits. Stimulus wavelength 648 nm.

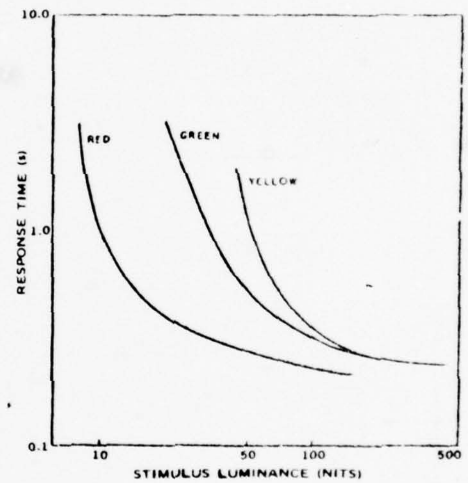


FIGURE 49.2. Subject's Response Time as a Function of Stimulus Luminance Using Broad Band Filters.

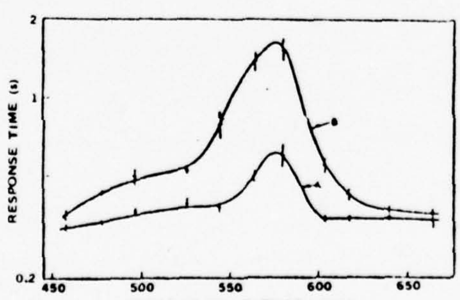
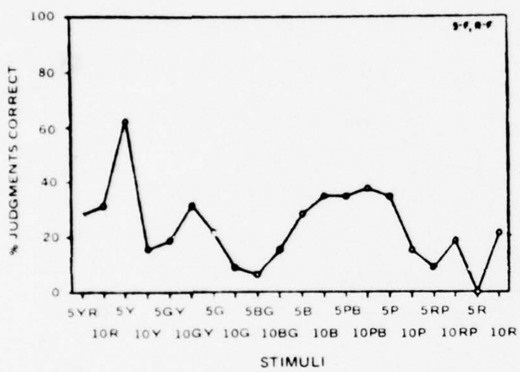


FIGURE 49.3. Subject's Response Time as a Function of Stimulus Wavelength. Stimulus luminances A:48 nits, B:30 nits.

50. Volkmann, Frances C. and T. Engen. "Three Types of Anchoring Effects in Absolute Judgment of Hue," *J. Exp. Psychol.*, Vol. 61 (1961), pp. 7–17.

Twenty equally spaced, low-saturation Munsell hues, plus two saturated hues were used as stimuli while 20 nonsense syllables, plus two highly associative syllables, were used as responses to investigate anchoring effects in hue judgment in terms of identification accuracy and response time. Anchoring effects are changes, "in one or more dependent variables." The authors found, in comparison with the control group who saw the nonanchored condition, that the anchoring stimuli were identified more accurately than the remaining 18 hues, but colors on either side were still not easily identified (only slight anchoring effect). Anchoring responses increased accuracy to the attached stimuli, but decreased it for surrounding stimuli. Anchoring stimuli seem to have a greater effect than anchoring responses. (See Figures 50.1 and 50.2.)



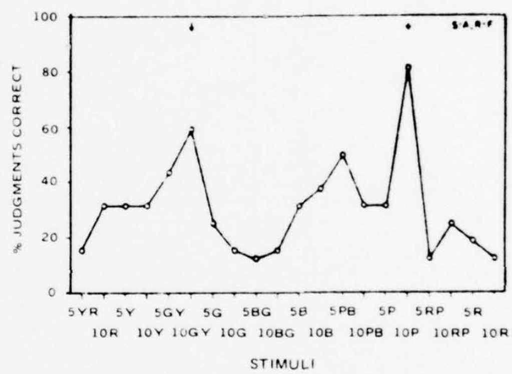


FIGURE 50.1. Percentage of Judgments Correct as a Function of Stimuli for Group S-F, R-F, the Control Group.

FIGURE 50.2. Percentage of Judgments Correct as a Function of Stimuli for Group S-A, R-F. Arrows at top of graph indicate the loci of supplied anchoring stimuli.

51. Wagner, Dan W. *Target Detection With Color vs. Black and White Television.* Naval Weapons Center, China Lake, Calif., NWC, April 1975. (NWC TP 5731.)

The author investigated target detection performance on color compared to black-and-white TV as a function of percent targets detected and detection time. Green, brown, and gray tanks were seen on a terrain model with two background colors (green and brown), under three levels of resolution (25, 35, and 300 TV lines) and three luminance contrast values (+0.3, 0, and -0.3). He found that: (1) Performance on color TV was slightly higher than on black-and-white TV (74 vs. 69%). (2) Background color was not significant, although it had an interactive effect. (3) Gray targets were significantly easier to detect. (4) Increased resolution had a comparable effect on color and black-and-white TV. (5) Targets lighter than the background (+0.3) were detected more often and faster than targets darker than the background (-0.3) or no contrast targets (0). (See Figure 51.1.)

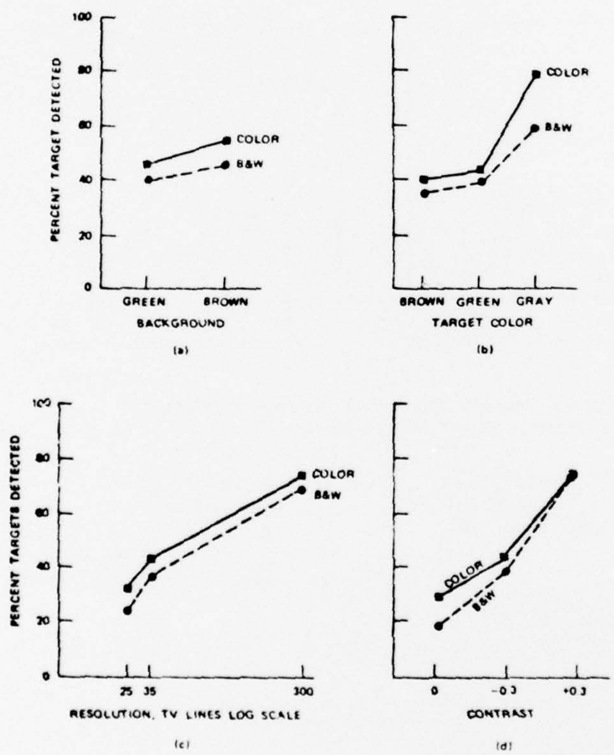


FIGURE 51.1. Percent Targets Detected With Color and Black-and-White TV as a Function of (a) Background, (b) Target Color, (c) Resolution, and (d) Contrast.

52. Wagner, Dan W. *Target Acquisition With Color vs. Black and White Television*. Naval Weapons Center, China Lake, Calif., NWC, October 1975. (NWC TP 5800.)

Two experiments were conducted, differing only in field of view (4.5 and 3.25 degrees), to investigate target detection and identification time and accuracy with color and black-and-white TV using realistic imagery. He found that: (1) Color TV was not significantly better than black-and-white TV. (2) Earth-colored targets provided better performance than green, brown, and olive targets. (3) Tanks were slightly easier to detect, but not identify, than trucks. (4) Target background had an interactive effect on both detection and identification. (5) The 3.25° FOV was better than the 4.5° FOV for detection (86 vs. 41%). (See Figure 52.1.)

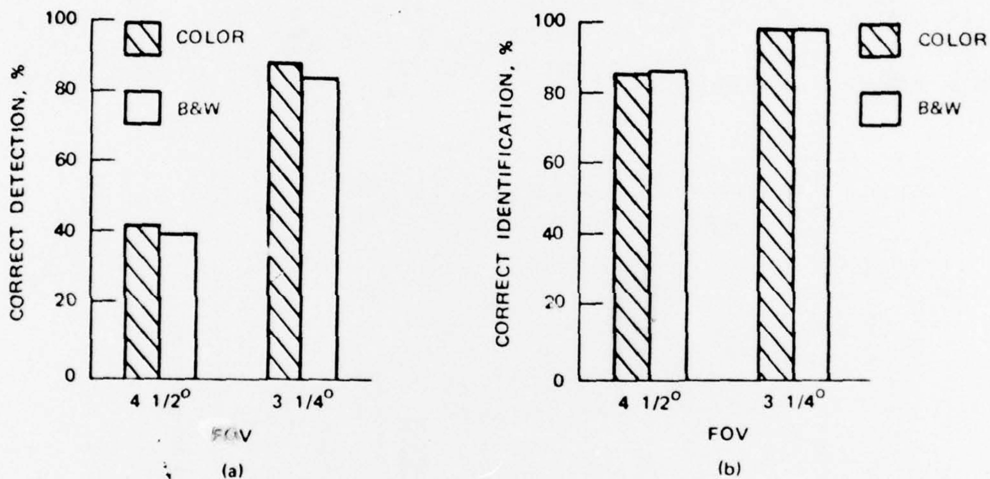


FIGURE 52.1. Percent Correct Detections (a) and Identification (b), Given Correct Detection, as a Function of Field of View for Color and Black-and-White Television.

53. Wagner, Dan W. *Experiments With Color Coding on Television.* Naval Weapons Center, China Lake, Calif., NWC, December 1976 (in preparation).

Three experiments were conducted which required subjects to detect vehicular targets on one TV display while monitoring one or two engine advisory TV displays, under red or white illumination (4.3 lux), for possible malfunctions. The advisory displays were seen in conventional black-and-white, monochromatic red, green, blue, and yellow, and two color-coded conditions (red malfunction indication shown against either yellow or white markings). The author found that (1) compared to black-and-white TV, response time was lower for the red-and-white color-coded condition and the monochromatic yellow or blue; response time was generally poorer with red or green monochrome, and little difference was noted for the red-on-yellow color-coded condition; (2) an advisory display in color (e.g., yellow) could be used with a black-and-white display without degrading performance; (3) the illumination color had no effect on performance, regardless of display color; and (4) when only one advisory display, seen in black-and-white or color-coded red-on-white, was used with the target detection task, target detection response time was significantly faster with the color-coded advisory display. There was no difference in response time between the color and black-and-white advisory display. (See Figure 53.1.)

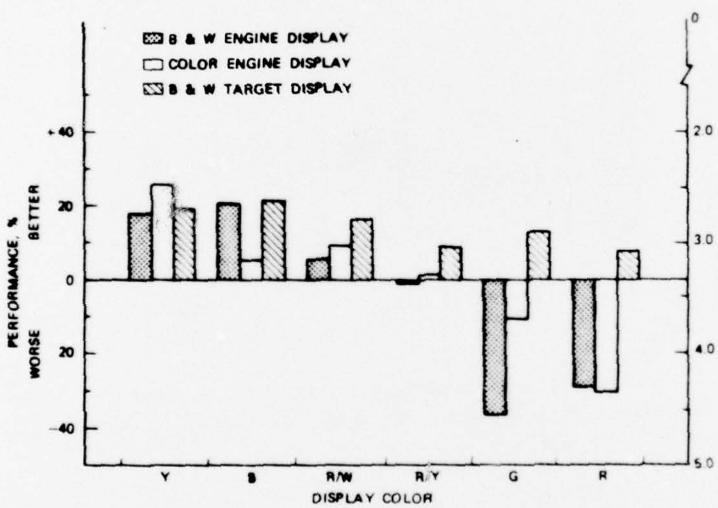


FIGURE 53.1. Color Relative to Achromatic TV Mean Response Time Performance for Three Displays.

54. Wedell, J. and D. G. Alden. "Color Versus Numeric Coding in a Keeping Track Task: Performance Under Varying Load Conditions," *J. Appl. Psych.*, Vol. 57 (1973), pp. 154–159.

Color versus numeric coding was investigated in an air traffic control-type (keeping-track) task–aircraft position, altitude, and identification. Subjects saw 6, 8, or 10 aircraft with number or color codes (6) to identify altitude level. They were periodically interrogated as to the number of aircraft (1, 2, or 3) at a particular level. The authors found that (1) errors increased with aircraft load; (2) errors increased with interrogation load (1, 2, or 3 aircraft at a given altitude); and (3) color was useful for retaining the number of aircraft at a particular altitude, but not superior to numerics for location or identity, especially at the higher loading levels.

55. White, R. M., Jr., M. J. Dainoff, and R. E. Reynolds. *Factors Affecting the Detection and Recognition of Colored Targets.* Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, AMRL, May 1972. (Technical Report 72-38.)

A series of five experiments were conducted to investigate target and background hue, saturation, brightness, size, position, ambient illumination, and absolute judgment effects on identification time and accuracy. Their findings generally substantiated existing literature in that hue, size, and brightness were effective variables in affecting performance. Additionally, it was found that: (1) Target colors complementary to the background color were most easily discriminated. (2) Saturation contrast (high saturation target versus low saturation background) provided faster reaction times than did luminance contrast. (3) Blue was an effective color in the periphery, but not the fovea of the retina. (4) When hue and saturation were varied individually and then jointly it was found that partial redundancy provided more accurate discriminability; but complete redundancy transmitted more information (2.93 bits). (See Figure 55.1.)

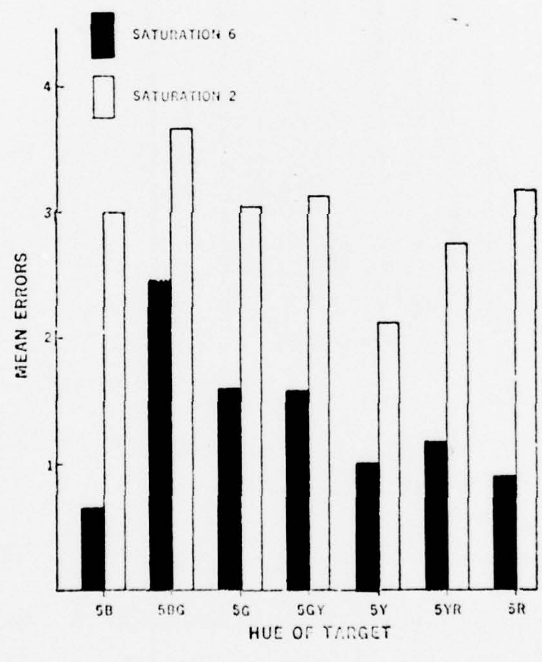


FIGURE 55.1. The Combined Effects of Hue and Saturation of Target Against Achromatic Backgrounds in Experiment I.

56. Wong, K. W., and N. G. Yacoumelos. "Identification of Cartographic Symbols From TV Displays," *Hum. Factors*, Vol. 15 (1973), pp. 21–31.

The authors investigated map symbol reading performance on color and black-and-white TV while varying map types (two line maps and one picto-map) and resolution (5, 7, and 9 lines/mm). They found that color TV had some advantages over black-and-white TV in that comparable performance was achieved with 25% lower resolution. Alphanumeric symbols were identified with nearly 100% accuracy at 9 lines/mm resolution. (See Figure 56.1.)

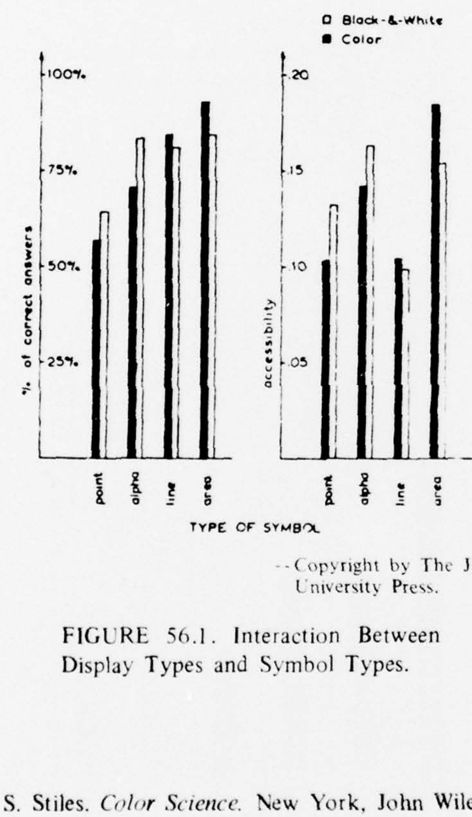


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FIGURE 56.1. Interaction Between Display Types and Symbol Types.

57. Wyszecki, G. and W. S. Stiles. *Color Science.* New York, John Wiley and Sons, Inc., 1967.

This fairly technical book contains some concepts and methods and a great deal of quantitative data and formulae. It assumes the reader has a technical background in color research and then provides the quantitative tools, in the form of tables, figures, and formulae, to accomplish that end. The book is divided into seven sections, including physical data on radiometry, the human eye, photometry, color and brightness matching, color discrimination, miscellaneous concepts, and a particularly coherent and informative section on colorimetry. (See Table 57.1.)

TABLE 57.1.

1. *Psychological concepts*

Term	Symbol	Geometrical Interpretation	Algebraic Expression and Relation to Other Terms
Color (perceived)	**C**	Point in three-dimensional space of color perception (Fig. 3.1)	—
Hue	ϕ	Cylindrical coordinates in three-dimensional space of color perception (Fig. 3.1)	—
Saturation	σ		—
Brightness, lightness	β		—
Chromaticness	γ	Colors of the same chromaticness lie on lines parallel to the brightness axis in space shown in Fig. 3.1	$\gamma = \gamma(\phi, \sigma)$

2. *Psychophysical concepts*

Term	Symbol	Geometrical Interpretation	Algebraic Expression and Relation to Other Terms
Color (psychophysical)	**Q**	Vector in three-dimensional space (Fig. 3.2)	$\mathbf{Q} = R\mathbf{R} + G\mathbf{G} + B\mathbf{B}$
Color stimulus	$\{P_\lambda\, d\lambda\}$	Values of a radiometric quantity, such as radiant flux per unit wavelength interval, plotted against wavelength (Fig. 3.3)	
Spectrum color	$\mathbf{Q}_\lambda$	Vector in three-dimensional space	$\mathbf{Q}_\lambda = R_\lambda\mathbf{R} + G_\lambda\mathbf{G} + B_\lambda\mathbf{B}$
Achromatic color	**N**	Vector in three-dimensional space	$\mathbf{N} = R_N\mathbf{R} + G_N\mathbf{G} + B_N\mathbf{B}$
Primary colors	**R, G, B**	Unit vectors along Cartesian coordinate axes of three-dimensional space (Fig. 3.2)	$\mathbf{R}(R = 1, G = B = 0)$, $\mathbf{G}(R = 0, G = 1, B = 0)$, $\mathbf{B}(R = G = 0, B = 1)$
Tristimulus values	R, G, B	Coordinates of vector **Q** in **R, G, B** space (Fig. 3.2)	$R = \int_\lambda P_\lambda \bar{r}_\lambda\, d\lambda$, $G = \int_\lambda P_\lambda \bar{g}_\lambda\, d\lambda$, $B = \int_\lambda P_\lambda \bar{b}_\lambda\, d\lambda$
Color-matching functions	$\bar{r}_\lambda, \bar{g}_\lambda, \bar{b}_\lambda$	Tristimulus values of monochromatic colors of equal radiant energy plotted against wavelength (Fig. 3.4)	
Chromaticity coordinates	r, g, b	Coordinates in chromaticity diagram	$r = \frac{R}{R+G+B}$, $g = \frac{G}{R+G+B}$, $b = \frac{B}{R+G+B}$; $r + g + b = 1$
Chromaticity	Q	Point in chromaticity diagram. (Intersection of vector **Q** with unit plane) (Fig. 3.2)	
Chromaticity diagram	—	Unit plane in **R, G, B** space (Fig. 3.2)	$R + G + B = 1$
Dominant wavelength	λ_d	See Fig. 3.6	
Complementary wavelength	λ_c (or $-\lambda_d$)		
Excitation purity	p_e	Ratio of distances in chromaticity diagram as shown in Fig. 3.6	$p_e = \frac{r - r_N}{r_b - r_N} = \frac{g - g_N}{g_b - g_N}$
Metameric colors	$\mathbf{Q}_1 = \mathbf{Q}_2 = \cdots$	Identical vectors in **R, G, B** space but different color-stimulus functions (Fig. 3.5)	$\int_\lambda P_{1\lambda}\bar{r}_\lambda\, d\lambda = \int_\lambda P_{2\lambda}\bar{r}_\lambda\, d\lambda = \cdots = R$; $\int_\lambda P_{1\lambda}\bar{g}_\lambda\, d\lambda = \int_\lambda P_{2\lambda}\bar{g}_\lambda\, d\lambda = \cdots = G$; $\int_\lambda P_{1\lambda}\bar{b}_\lambda\, d\lambda = \int_\lambda P_{2\lambda}\bar{b}_\lambda\, d\lambda = \cdots = B$; with $P_{1\lambda} \neq P_{2\lambda} \neq \cdots$
Isomeric colors	$\mathbf{Q}_1 \equiv \mathbf{Q}_2 \equiv \cdots$	Identical vectors in **R, G, B** space and identical color-stimulus functions	$P_{1\lambda} \equiv P_{2\lambda} \equiv \cdots$

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